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by

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Submitted in partial fulfillment
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PREFACE

In the past few years the Navy has been making a serious effort to decrease the size and weight of all electrical and electronic equipment destined for installation in aircraft, and also to increase their reliability under normal operating conditions. An examination of data concerning new aircraft will indicate why this has become important. Todays modern jet fighter weighs nearly as much as some World War II bombers. Much of this increase in weight may be attributed to the large amount of electronic and electrical equipment which has been placed in the aircraft; at present the growth factor for a new aircraft is approximately seven pounds of additional airframe, engine and fuel for each pound of equipment added. If some method could be devised to reduce the size and weight of the electrical system of an aircraft, it would be very advantageous to the airframe manufacturer and to Naval Aviation in general.

One method of reducing aircraft electrical system weight, now under investigation, involves replacing the direct-current power distribution system with an alternating-current system. However even an aircraft with an alternating-current electrical system requires approximately ten percent of its generated power to be converted to direct current (1). This means the use of either a rotary converter or transformers and semiconductor rectifiers. The latter method is the more reliable since it requires no moving parts other than a possible cool-

ing fan; however, the space and weight factor make it less desirable.

In 1955 several rectifier systems designed for 60 cycle per second alternating current were installed in industry using a new germanium power rectifier. These had a weight reduction of four to one and a volume reduction of 40 to one over selenium rectifiers of comparable power rating (2). Dallas and Reising (3) have proposed a conversion system for for aircraft using selenium rectifiers but no transformers, thus removing a large portion of the weight and volume. If the above mentioned germanium rectifiers that have proved successful at 60 cycles per second could be utilized in aircraft at 400 cycles per second, an additional savings in weight and volume could be obtained.

The purpose of this thesis is to investigate the properties and characteristics of a germanium power rectifier designed for 60 cycles per second but operated at 400 cycles per second. Three different stock rectifiers were obtained and tested to varying degrees.

The work on this thesis was done in the fall of 1955 and the spring of 1956 at the United States Naval Postgraduate School, Monterey, California under the direction and guidance of C. H. Rothauge, Associate Professor of Electrical Engineering. To him the author is greatly indebted for all help and assistance which he has so cheerfully given.

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LIST OF ILLUSTRATIONS

TABLE OF SYMBOLS

(Listed in the order of their use in the text)

$^{\circ}C$	degrees centigrade
S	a switch
I	current, a.c. or d.c.; also an ammeter
V	a voltmeter
R	resistance or resistive load
μ	micro, or 10^{-6}
ma	milli amperes
$\sim$	cycles per second; or alternating-current source
i_b	current through a diode or a rectifier
e_b	voltage drop across a diode or rectifier
α_t	temperature coefficient of resistivity
f_r	temperature correction factore
ufd	micro farads
γ	ripple factor
L	inductive load
ϕ	phase
η	efficiency

CHAPTER I

INTRODUCTION

1. Basic concepts.

Whereas the metallic rectifier as we now know it can be desribed as a recent developement, the phenomenon of asymmetric conduction has been studied for a long time. The properties of metal rectifiers are now known to be affected by a large number of manufacturing and operating conditions. Even now, however, the exact significance of a change in these conditions is not always perfectly understood.

Germanium rectifiers are a very recent developement (6), and the available amount of well-confirmed information concerning their manufacture and properties is still comparatively small. Many war-time applications demanded the use of reliable crystal diodes, giving good rectification and capable of operating over a wide range of temperatures. Germanium rectifiers were developed in order to meet this need. From this beginning it was a logical step to extend their application to the field of power rectification.

The metallic rectifier is a static device for converting alternating current into direct current. It makes use of a highly unusual property of certain materials which allows current to flow in only one direction. There have been a number of theories advanced to explain this uni-directional property such as: (a)Thermal Diffusion Theory, (b) Theory of Physical

Barrier Layer, (c) Theory of Discontinuous Space Charge, and many more (4). It is not the object of this thesis to explain these theories. Germanium power rectifiers are usually best explained by the barrier layer theory which is adequately covered in reference (7).

The pure metallic germanium does not have all the required qualities of a rectifier. The designation "P" type and "N" type germanium is currently being used to describe the actual structure as used in a rectifier. This simply means that some impurity or unbalance of the atomic structure is necessary to produce free electrons. Experiment has proven that alloying with indium produces "P" type germanium and alloying with antimony produces "N" type germanium. When put into a commercial unit, the germanium rectifier is a sandwich of five layers of material fused together. Top and bottom layers are of molybdenum, which has the same thermal expansion as germanium and has good heat conductivity. These layers provide strong stable support for the other layers during manufacture and provide good surfaces for attaching the electrical connections. The rectifying and center layer of the cell is a thin slice of germanium from a single crystal; this slice contains the small amount of impurity, which produces an excess of electrons and makes the germanium "N" type. The germanium is soldered to the bottom molybdenum layer with pure tin and to the top molybdenum layer with pure indium. The molybdenum to tin connection is ohmic, but the indium on

the top surface forms a P-N junction by diffusing into the germanium and changing its upper surface from "N" to "P" type. This permits easy current flow from "P" to "N" but deters current flow from "N" to "P". The crystal assembly is soldered to a metal base and has a flexible cable soldered to its top.

The wafer is usually sealed, for moisture is one of the most deleterious impurities; it increases the reverse leakage current at the edge of the junction.

As is well known, the operation of a metal rectifier is limited within certain maximum values of applied voltage and current. If these limits are exceeded the rectifier "breaks down", that is, its forward and reverse resistance tend to equalize and the disk thus becomes useless for rectification purposes.

The mechanism of rectifier breakdown is frequently misunderstood and, in particular, is often regarded as corresponding to the dielectric breakdown of an insulator. Actually rectifier breakdown is nearly always due to excessive heat accumulation which results from ohmic loss in the semi-conducting film and the barrier layer. The semi-conductor is never of perfectly uniform thickness and thus regions of lower resistance, and hence higher current densities and excessive heating, always occur. one way in which breakdown can occur applies to the case of prolonged exposure to a temperature which is insufficient to melt the electrodes, but is sufficient to cause a considerable increase in the mobility of the

impurity centers. The advantageous distribution of impurities which was achieved during the electrical forming process is then destroyed and the efficiency of the rectifier rapidly decreases until nearly all asymmetry of conduction disappears.

Under all conditions of operation the resulting temperature rise depends on the nature of the assembly as well as the losses in the rectifier disks. In particular the size of the cooling fins and the distance between these fins are of great importance in this respect. One objective of this thesis was to determine if this fin size and spacing as designed for 60 cycle operation was adequate for 400 cycle operation.

2. Test items.

Three types of germanium rectifiers were obtained and tested. Type 1 rectifier consisted of six matched rectifier disks in a three phase bridge circuit. Each rectifier connection was brought out to a terminal strip and jumpers were used to form the desired bridge circuit. Thus by proper manipulation of the jumpers a single rectifier could be operated alone or any desired circuit formed. This rectifier was manufactured by the General Electric Company and designated type 4JA3011BF1AB1 (see appendix D for the specifications). It is rated at five amperes direct current per cell, and at maximum peak inverse voltage of 200 volts, both ratings at 70°C fin temperature. These were the direct current limits used for all tests. During alternating-current operation using a single phase full wave circuit, ten amperes effective was

used as full load current. This gave a value of five amperes effective from each rectifier. An inverse voltage of 140 volts effective was set as the maximum. This gave a peak inverse voltage of 200 volts. Most tests were made with single phase alternating current to obtain the characteristics of the rectifier. The author realizes that the three phase bridge operation has certain advantages and these have been discussed in Chapter III, Section 2.

The type 2 rectifier consisted of a single cell made by the General Electric Company, model number 6RA2DF1. It was rated at eight ampers direct-current output and at 65 volts effective alternating-current input.

The type 3 rectifier was also a single cell made by the General Electric Company, model number 6RA2CF1. It was rated at 12 amperes direct-current output with 50 volts effective input. Rectifiers 2 and 3 were very similar and when operated as a pair, the direct current of each was limited to eight amperes and the alternating current to eight amperes effective (see appendix D for the specifications).

Tests were made on the three rectifiers using direct current, 60 and 400 cycle per second alternating current. In the conclusions, Chapter V, comparisons are made only between the 60 and 400 cycles per second tests to determine the effect of the increased frequency. The tests conducted included the determination of the effects of time and temperature on the conduction of the rectifiers; the forward and reverse volt-

ampere characteristics; resistance; regulation; and efficiency.

3. Summary of results.

In no case investigated was 400 cycles per second detrimental to the operation of the rectifier. The effects of both time and temperature were found to be nearly identical for operation at both 60 and 400 cycles per second. There was a small change in the volt-ampere characteristics with the use of 400 cycles per second but it is concluded that the effect is negligible. The regulation and efficiency were the same as for 60 cycles per second while the addition of a filter capacitor across the output made the regulation and efficiency much better than for 60 cycles per second. Such a filter capacitor would only be used for single phase operation. For three phase operation the filter capacitor would not be necessary hence 400 cycles per second would have no advantage over 60 cycles per second.

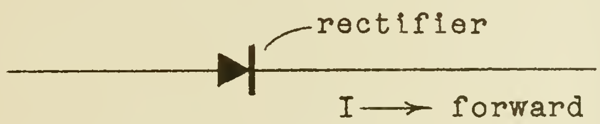
In conclusion the author sees no reason why germanium power rectifiers as now manufactured for 60 cycles per second industrial power could not be utilized for 400 cycles per second aircraft power. The author believes that further studies should be made before a final approval can be given. These studies could include: the measurement of rectifier self capacitance; the effect of extremely cold temperatures; and the transient effects of suddenly applied or removed loads.

CHAPTER II

CHARACTERISTICS

1. General.

Probably the one most important piece of information about a rectifier is its V-I curve, voltage versus current. In the forward direction it is the voltage drop across the rectifier for a given load current that is of interest; while in the reverse direction it is the leakage current through the rectifier for a given applied voltage. Forward direction implies that current is flowing in the direction of least resistance, the direction for which the rectifier is approximately a short circuit. The symbol used is:



The reverse direction implies current flow in the direction of high resistance. For alternating-current power sources, the instantaneous current is considered.

Before any other data could be taken, it was necessary to determine what effect time had on the conduction of each rectifier. With this information on hand, it was known when to take measurements after the power had been applied.

Since it is known that temperature has a pronounced effect upon the resistance of a semi-conductor, it was necessary to determine this effect. The temperature of the rectifiers was held as near 22°C as possible. If it had previously

been determined that the temperature was critical for a test, temperature corrections were applied to the data for which the temperature was not 22°C.

2. Direct-current volt-ampere characteristics.

The direct-current characteristics were straight forward and easy to obtain. The circuit shown in Fig. 1 was used for

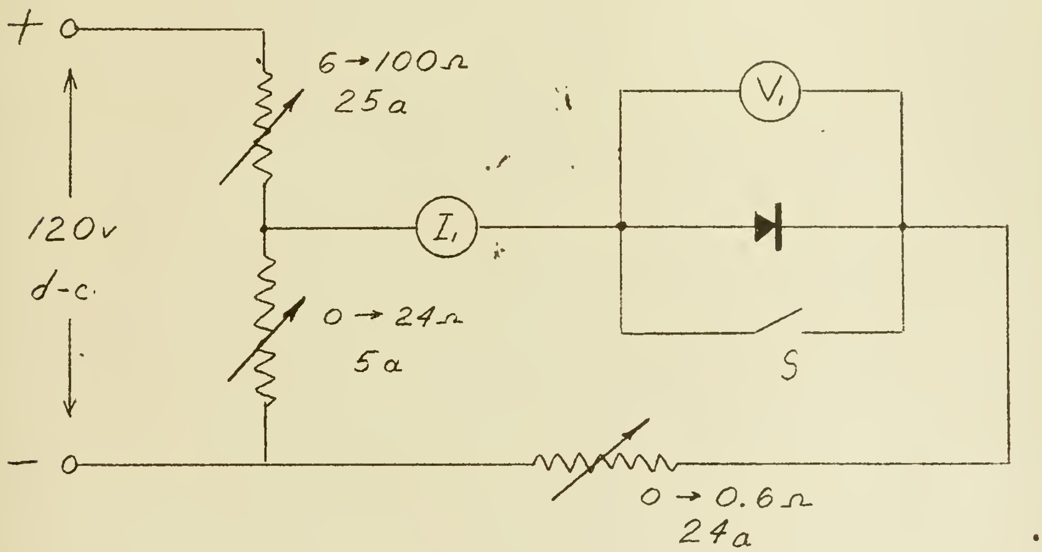


Fig. 1. Circuit used to obtain the forward direct-current volt-ampere characteristic.

the forward direction. The switch S was closed until the current I_1 was of approximately the proper magnitude. This was for additional safety. By means of the variable resistors, forward current was varied from zero to the maximum value for each rectifier; i.e., ten amperes for rectifier 1. The forward current, the voltage drop across the rectifier, and the temperature of the rectifier were recorded for each current setting. The resulting forward volt-amper curves are shown in

Fig. 29 for rectifier 1 and in Fig. 30 for rectifiers 2 and 3. It will be noticed that the characteristic curves for rectifiers 2 and 3 are nearly identical in the forward direction. It is in the reverse direction where these two rectifiers differ.

For the reverse direction the circuit of Fig. 2 was used. The switch was left open during the adjustment of R until the voltage V did not exceed the peak inverse voltage rating of the rectifier. The voltage V across the rectifier, the reverse

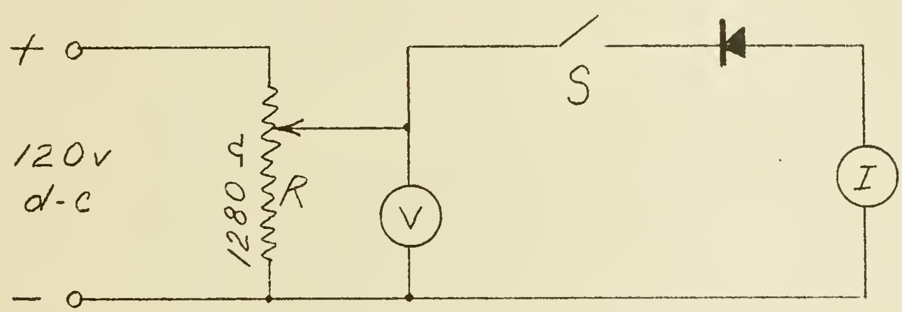


Fig. 2. Circuit used to obtain the reverse direct-current volt-ampere characteristics.

current through the rectifier I (leakage current), and the temperature were recorded for each setting of V while V was varied from zero to the maximum peak inverse voltage for each rectifier (200 volts for rectifier 1), The resulting volt-ampere curve for rectifier 1 is shown in Fig. 31. Two curves are shown representing data taken on two widely separated days to check reproducibility. The results for rectifier 2 are shown in Fig. 32 and for rectifier 3 in Fig. 33. It is

important to note the difference in current scales for each of the three rectifiers.

3. Alternating-current volt-ampere characteristics.

The circuits used for the direct-current characteristics were not suitable for the alternating-current characteristics measurements. Every half cycle the rectifier has an inverse voltage across it, thus a voltmeter-reading across the rectifier would be proportional to this inverse voltage and not the smaller forward voltage drop. Likewise an ammeter in series with the rectifier would read the forward current and give no indication of the much smaller reverse current.

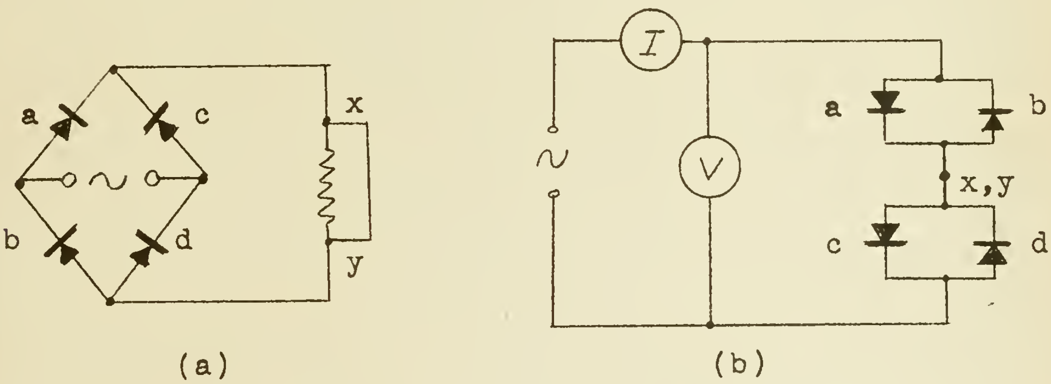


Fig. 3. Single phase bridge circuit with shorted output terminals.

For measuring the voltage drop in the forward direction, the method outlined by Henisch (4) known as the "short circuit test" was used. This can be visualized as a single phase full-wave bridge circuit as in Fig. 3(a) with the output terminals x,y shorted. The circuit can be redrawn as in Fig. 3(b). Only one pair of rectifiers is needed, a and b. During

one half cycle of applied voltage rectifier a acts as a low impedance and the current through the ammeter is the forward current through rectifier a plus the negligible reverse current through rectifier b. The reverse current through one rectifier will be in the order of 1/100,000 of the forward current through the other rectifier at any one time. The voltage drop across the pair of rectifiers is the forward voltage drop across rectifier a. During the next half cycle the applied voltage reverses and now rectifier b is a low impedance. The current through the ammeter is the forward current through rectifier b and the voltage drop across the pair is the forward voltage drop across rectifier b. Thus if the two rectifiers are matched, the ammeter reads the effective value of the forward current through each rectifier and the voltmeter reads the effective value of the forward voltage drop across each rectifier.

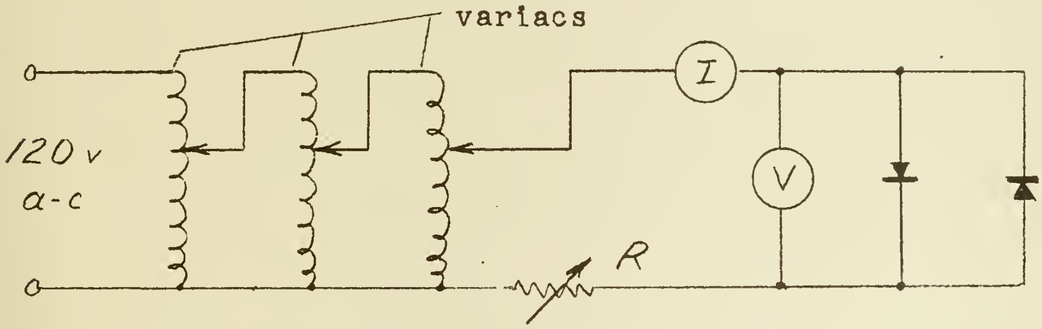


Fig. 4. Circuit used to obtain the forward alternating-current volt-ampere characteristic.

The actual circuit used for the forward alternating-current characteristic tests is shown in Fig. 4. The three

variacs were used to give a fine control over the applied voltage. The dropping resistor R was used to allow the variacs to work at a higher output voltage for better stability of settings.

The resulting forward characteristics for rectifier 1 for both a 60 and 400 cycle per second power source are shown in Fig. 34. In addition, six rectifiers of type 1 were connected as in Fig. 5 to form a "short circuit test" for a three

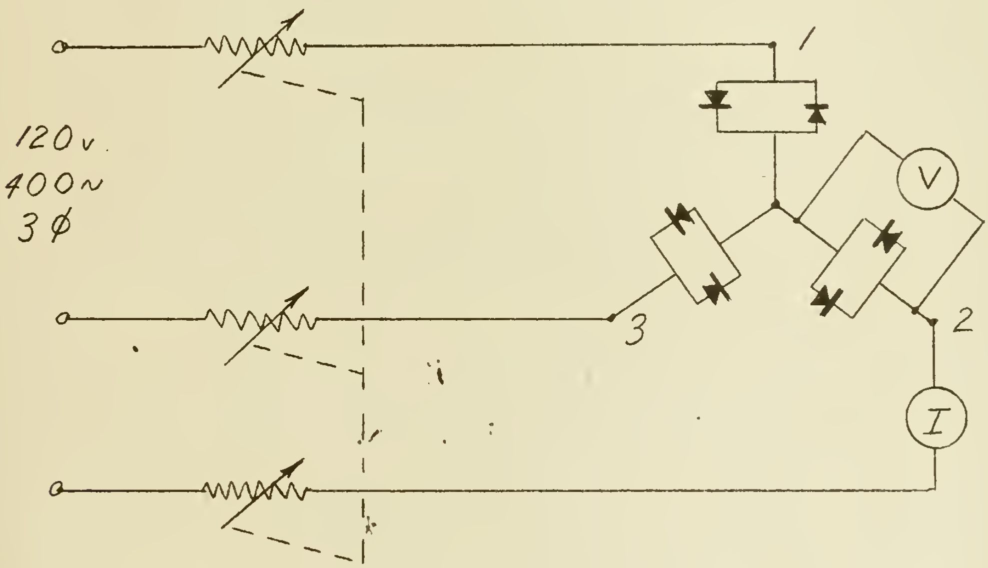


Fig. 5. Circuit used to obtain the forward three phase volt-ampere characteristic.

phase bridge. The forward volt-ampere characteristic for this three phase rectifier is also shown on Fig. 34.

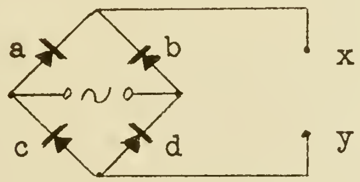
Fig. 35 shows the forward volt-ampere characteristic of rectifiers 2 and 3 in a short circuit test. This was possible with these two rectifiers since it was shown in Fig. 30 that they had very similar forward characteristics; however, they

are not matched in the reverse direction.

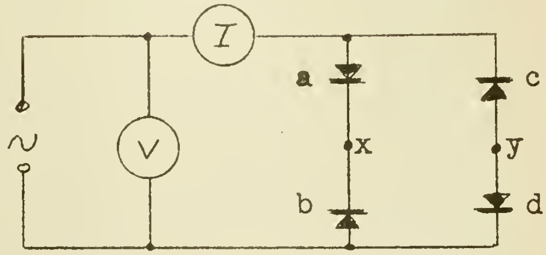
Fig. 47 shows photographs of the forward volt-ampere characteristics of rectifier 1 for 60 cycles per second. Fig. 48 shows the same for 400 cycles per second. Figs. 47(a) and 48(a) are for a full load current of ten amperes. In Figs. 47(b) and 48(b) the load has been reduced to five amperes with no change in gain settings of the oscilloscope. It will be noticed that for the actual alternating-current characteristic, the upward swinging trace and the return trace do not coincide. The higher the frequency, the more pronounced these loops become; also the higher the load current, the larger the separation between traces. The exact mechanism of this phenomenon is not yet understood, but it is probably connected with the inter-action between the voltage-dependent resistance and the voltage-dependent self-capacitance of the rectifier.

For measuring the current in the reverse direction, the "open circuit" method (4) was used. This can again be visualized as a single phase full-wave bridge circuit as in Fig. 6(a) with the output terminals x,y open circuited. The circuit can be redrawn with two parallel paths as in Fig. 6(b). Only one of these paths is required during the test. During one half cycle of the applied voltage, rectifier a acts as a low impedance but rectifier b acts as a very high impedance. Essentially all of the applied voltage as read by the voltmeter will be across rectifier b as an inverse voltage. An

examination of the foreard characteristic will disclose that the voltage drop across rectifier a is essentially zero with less than one milli-ampere of current flowing in the forward



(a)



(b)

Fig. 6. Single phase bridge circuit with open output terminals.

direction. The high impedance of rectifier b will be the limiting factor for the current and thus the ammeter will read only the reverse current of rectifier b. During the other half cycle the functions of the two rectifiers will be reversed and if the rectifiers are matched the voltmeter reads the inverse voltage across a single rectifier and the ammeter the reverse current.

The actual circuit used for the reverse alternating-current characteristic tests is shown in Fig. 7. Because the reverse current was only a few micro-amperes, current readings were taken by means of the voltage drop across a known non-reactive resistor.

The resulting reverse characteristics for rectifier 1 for both a 60 and 400 cycles per second power source are shown in Fig. 36.

Fig. 49 shows photographs of the reverse volt-ampere characteristic of rectifier 1 for 60 cycles per second. Gain settings were held constant and only the applied inverse voltage decreased. Fig. 50 shows the actual reverse volt-ampere characteristic of rectifier 1 for 400 cycles per second. Again

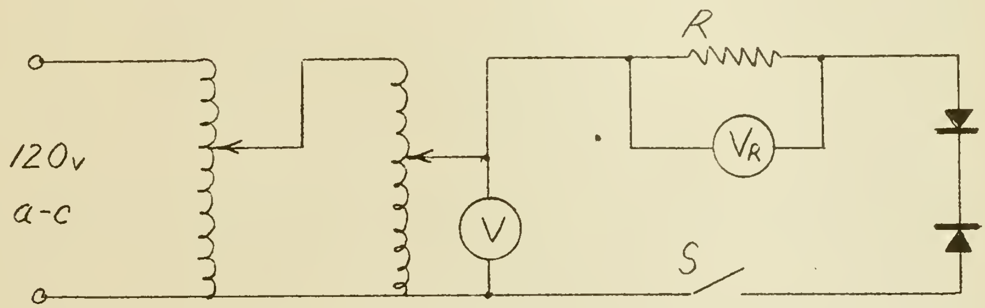


Fig. 7. Circuit used to obtain the reverse alternating-current volt-ampere characteristics.

the separation of the traces is clearly evident and shows the effect of frequency and applied voltage.

Examination of Fig. 34 indicates that the forward volt-ampere characteristic curve for a germanium rectifier has the same general shape as that for a vacuum tube diode rectifier.

It is known that, provided the initial velocities of the electrons are neglected, the plate current of a diode is given by a relationship of the form

$$i_b = Ke_b^{3/2}.$$

This relationship is known as Child's Law. The initial electron velocities due to thermionic emission are very small in

comparison with the final velocities if the plate voltage is of high enough potential to cause sufficient acceleration. At low plate voltages the initial and final velocities are of the same order of magnitude and Child's Law does not hold. It is obvious from Fig. 34 that some such power law may hold for the germanium rectifier.

It was found that the relationship

$$i_b = 20\, e_b^{3.2}$$

gave a curve which approximated very closely the 60 cycle per second curve of Fig. 34. See Fig. 37.

Here again the relationship does not hold for low values of voltage. The current through the rectifier is essentially zero until the applied voltage across the rectifier reaches a definite value. This potential imparts sufficient energy to the free electrons to enable them to over come the forbidden energy levels. This is analogous to the concept of overcoming the work function of a metal.

For the 400 cycle per second curve the exponential power factor was found to be the same; but the constant was decreased.

$$i_b = 18\, e_b^{3.2}$$

gave a good approximation as shown in Fig. 38.

It is thus possible to approximate the germanium forward volt-ampere characteristic by an equation which for practical purposes is independent of frequency at the lower frequencies.

A value of K such that

$$i_b = 19\, e_b^{3.2}$$

shown on both Fig. 37 and Fig. 38 illustrate this.

4. Resistance.

There are two types of resistance, D.C. and A.C. The D.C. resistance at any point on the characteristic curve is defined as the voltage divided by the current at that point,

$$R_{d.c.} = \frac{E}{I}.$$

For an alternating-current power source, the effective voltage and current are used. This gives an equivalent resistance which can be used to replace the rectifier to give the same voltage drop for a specified load current. When the resistance is obtained from the forward characteristic curve it is called the forward resistance. When the reverse characteristic curve is used, it is called the back resistance.

The A.C. or dynamic resistance is defined as the slope of the curve at that point,

$$R_{a.c.} = \frac{dE}{dI}\ .$$

The rectifier can then be thought of as being biased by a direct-current voltage equal to the effective voltage at the operating point on the characteristic curve. The slope of the curve at this point is thus an equivalent resistance for a small amplitude alternating voltage operating about this biased point. This is analogous to the characteristic curves of a triode where the dynamic plate resistance is the slope

of the curve at an operating point and the operating point is determined by the bias on the tube.

The D.C. resistances were calculated from the characteristic curves for direct-current and 60 and 400 cycle per second alternating current. The results are shown in Figs. 39 and 40. It can be noted that in the forward direction the D.C. resistance is nearly identical for each of the three types of power.

The A.C. resistances were calculated for only 60 and 400 cycle per second alternating current. The results are shown in Figs. 41 and 42. It can be noted that in the reverse direction the rectifier has a maximum resistance at about 40 to 50 inverse volts.

The ratio of back to front resistance is often taken as one method of rating a semi-conductor rectifier. For rectifier 1 the A.C. resistance at the rated peak inverse voltage of 140 volts and the resistance at the rated forward current of ten amperes was used to give the following back to front resistance ratios:

60 cycles per second ----- 44,500,000 to 1

400 cycles per second ----- 53,500,000 to 1

Using the maximum back resistance and the minimum forward resistance, the following values were obtained:

60 cycles per second ----- 121,000,000 to 1

400 cycles per second ----- 127,000,000 to 1

5. The effect of time.

For the forward direction, the rectifier was placed in operation conducting a constant current and the voltage drop across it was recorded as a function of time after applying power. This was done for direct current, 60 and 400 cycle per second alternating current. The circuit used for the direct-current case is shown in Fig. 1, and the basic method was the same as that outlined in section 2 for the forward volt- ampere characteristic. For the alternating-current case, the circuit of Fig. 4 was used and the method outlined in section 3 for the forward volt-ampere characteristic.

In all cases and for all rectifiers, the forward voltage drop was constant with time. See Tables I through V.

For the reverse direction the rectifier was placed in operation with a fixed inverse voltage across it and the leakage current recorded as a function of time. The circuit used for the direct-current case is shown in Fig. 2 and the basic method used was the same as that outlined in section 2 for the reverse volt-ampere characteristics. For the alternating-current cases, the circuit is shown in Fig. 7 and the method outlined in section 3. For rectifier 1 there again was no effect of time. See Tables VI, VII and VIII. The slight variation in reverse current was found due to changes in temperature. For both rectifiers 2 and 3 there was a definite "creep" of reverse current with time. This is clearly shown in Fig. 13 for rectifier 3. For an additional test a constant

inverse voltage was applied to the rectifier and held until the reverse current had become nearly steady. The power was then removed for a short period of time, and reapplied. This was to determine to what value the current would return. The results are shown in Figs. 14 and 15. The period the power was off was varied and also the inverse voltage being reapplied. Fig. 14 also shows the effect of a sudden increase in voltage without shutting down the power.

During the first five or ten minutes a rectifier was on, the peak reverse current was found to be a function of how long the rectifer had previously been sitting idle with no power. A rectifier that had not been used for several days had a higher reverse current during the first few minutes of use than one that had been idle for only a few hours. This is clearly shown in Fig. 16 where the rectifier drew more reverse current with 50 volts across it after sitting idle for seven days than it did with 70 volts across it after sitting idle for only 20 hours.

Because the reverse current changed during the first few minutes after the application of power, any tests made using a fixed voltage were made after the rectifier had been warmed up at that voltage for at least an hour. If the input voltage was to be an independent variable the tests were made in such a manner that all readings were taken at exactly one minute after a change in voltage had been made. This helped insure that successive readings would be comparable. Of course this

precaution was not necessary with rectifier 1 because there was no "creep" of current.

6. The effect of temperature.

The temperature measured was that of the cooling fin immediately adjacent to the rectifier junction. Measurements were made by means of an iron-constantine thermo-couple using ice-water in a Dewar Flask as a reference point. The indicating device was a Weston Model 440 galvanometer with 60 divisions for full scale and calibrated to read from zero to 60 degrees centigrade. The same circuits and methods were used as for measuring the volt-ampere characteristics in sections 2 and 3. See Figs. 1, 2, 4 and 7.

For the forward direction a constant current was maintained through the rectifier and the voltage drop across the rectifier recorded as the temperature was varied. A combination of a variable speed direct-current electric fan and a heat lamp were used to get any desired temperature from 20°C to 60°C. It can be noted from the resulting curves shown in Figs. 17 through 22 that the forward voltage drop decreased as the temperature increased indicating a negative temperature coefficient of resistivity, α_t. It will also be noted that the decrease was linear.

In the reverse direction the voltage was held fixed and the reverse current recorded as the temperature was varied. For rectifiers 2 and 3, a one hour warm up was required to eliminate the time variable. The results shown in Figs. 23

through 27 indicate that the current increases with an increase in temperature, again a negative temperature coefficient of resistivity, α_t. Here the rate of change is non-linear with the current increasing more rapidly as the temperature is increased.

The results of these "effect of temperature" curves were used to correct any observed data to a standard temperature of 22°C. This value was chosen because it represented the average room temperature and thus corrections were kept to a minimum. For those tests decribed in other sections, the fan was used continually to keep the rectifier temperature as near 22°C as possible. An example of the method of correcting for temperature is shown in Table XXV and Fig. 28. Here the current I_T at any temperature T is divided into the current I at 22°C to give a correction factor. This correction factor, f_r, is plotted versus temperature in Fig. 28. Thus for all future direct-current work on rectifier 1, the reverse current I_T at any temperature T can be corrected to the value it would have been at 22°C, I_{22}. This is done by multiplying I_T by the correction factor f_r for the temperature T from Fig. 28.

The temperature to which rectifier 1 would rise using no forced air cooling was also checked. This was done using alternating current only. It was first done using 60 cycles per second, 400 cycles per second, and 400 cycles per second three phase while the rectifiers were connected for the "short circuit test" described in section 3. The results are tabulated

in Table XXVI. The rectifiers were next connected for normal full wave rectification as in Fig. 8 using both resistive and inductive loads; with and without a filter. A full load of ten amperes direct current was established and the final steady state temperature recorded in Table XXVI.

CHAPTER III

REGULATION

1. No filter.

To determine the regulation of the rectifier, the full wave rectifier circuit of Fig. 8 was used. The voltage V_1 across the secondary of the transformer was held at 120 volts

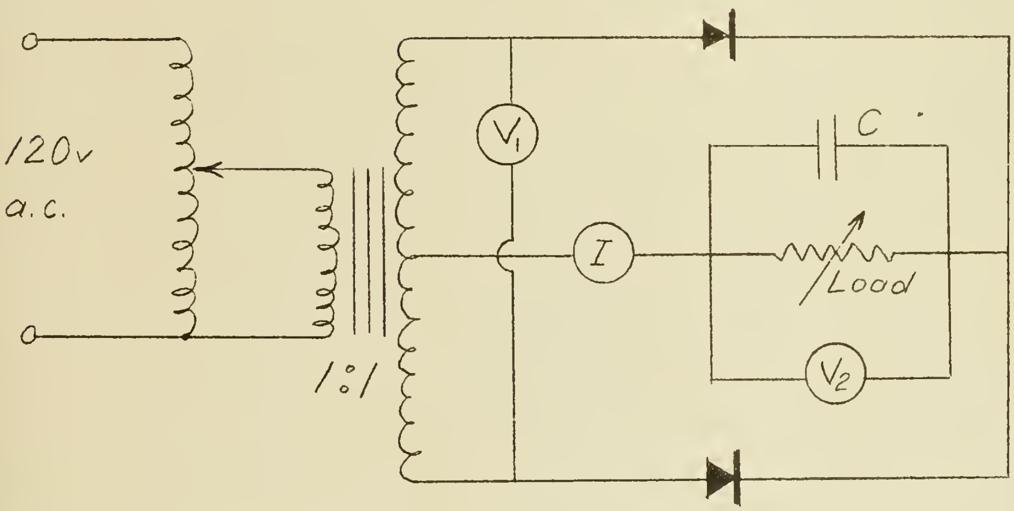


Fig. 8. Full wave rectifier circuit used to determine regulation.

effective, putting 60 volts across each rectifier in the forward direction. The inverse voltage across each rectifier was 120 volts effective and controled the maximum input voltage that could be used. Fig. 9 shows that the maximum direct-current voltage that can be obtained is 54 volts. Fig. 43 shows the full load output voltage to be 51.8 volts for 60 cycles per second input or a regulation of 96 percent, where percent

regulation is defined as

$$\frac{\text{D.C. output, full load}}{\text{D.C. output, no load}} \times 100.$$

Fig. 43 also shows the full load output for 400 cycles per second to be 52.4 volts or 97 percent regulation. The no filter regulation curve is linear and very flat. Figs. 51 and 52 show that the voltage across the load and the rectifier current are both rectified sine waves with no distortion.

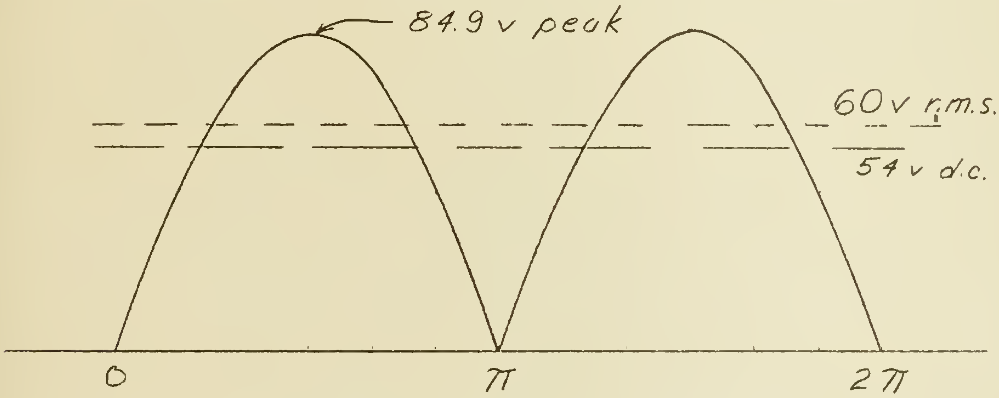


Fig. 9. Average value of a full wave rectified sine wave.

2. With filter.

A filter composed of a 240 micro-farad capacitor across the load was used next. As shown in Fig. 43 the effect on regulation was much more pronounced with 400 cycles per second than with 60 cycles per second. The theoretically possible no load voltage is now the peak voltage 84.9 volts. The full load voltage for 60 cycles per second is 52.8 volts giving a 62.8 percent regulation. Fig. 53(a) shows the voltage waveform across the load. The ripple factor for this wave is

0.483 where ripple factor is defined as :

$$\gamma = \frac{\text{Effective value of the alternating component}}{\text{Direct or average value}}$$

Fig. 53(b) is for the same circuit but the load has been reduced to 1.2 amperes giving a ripple factor γ = 0.150.

The full load voltage for 400 cycles per second is 63.1 volts giving a 74.2 percent regulation. See Fig. 43. Fig. 54(a) shows the full load wave form and Fig. 54(b) the wave form with 1.28 amperes. The ripple factor is 0.098 and 0.018 respectively.

Figs. 55 and 56 show the combined current I from the two branches of the rectifiers at 60 and 400 cycles per second with full and partial loads. It is evident that there is a period during each half cycle when neither rectifier is conducting and load current is being supplied by the capacitor. However since average output current remains the same, the peak current must increase. Fig. 55(a) shows that for a full load of ten amperes direct current, a peak current of 15.07 amperes flows through the rectifier. If the average load current is reduced by a factor of 8.3 to 1.20 amperes as in Fig. 55(b) the peak current is reduced only by a factor of 2 to 7.46 amperes. With 400 cycles per second, for a load current of ten amperes, a peak current of 22 amperes flows through the rectifiers.

The filter capacitance was increased to 550 micro-farads.

The effect on the operation at 400 cycles per second was insignificant, but there was an increase in regulation for the conditions at 60 cycles per second. See Fig. 43. The effect on ripple factor is clearly shown in Figs. 57 and 58. Although the additional capacitance did not change the regulation for 400 cycles per second, it did improve the ripple factor. Figs. 59 and 60 show the rectifier current with 550 micro-farads capacitance. Comparison of Figs. 56 and 60 shows that the increase in capacitance had no effect on the current wave shape with 400 cycles per second. Comparison of Figs. 55 and 59 shows that with 60 cycles per second the additional filter capacitance caused a narrower and sharper pulse of current from the rectifier. Again the peak current increased to maintain the same average current.

Operation at 60 cycles per second with a 550 micro-farad capacitor had a regulation of 68.1 percent. Using the 400 cycle per second power source and decreasing the capacitance it was found that only 58 micro-farads were required to give the same 68.1 percent regulation. The full load ripple factor for 60 cycles per second with 550 micro-farad capacitance was 0.392. It required only 61 micro-farads to give the same ripple factor for 400 cycles per second. See Fig. 61. Fig. 44 shows the effect of capacitance on output voltage and ripple factor for the rectifier system when operated at 400 cycles per second.

The resistive load was replaced with an inductive load

consisting of a direct-current motor driving a loaded generator. The 550 micro-farad filter capacitor was used. The regulation curve at 400 cycles per second was identical to that for a resistive load and 550 micro-farads. The regulation curve at 60 cycles per second was not the same as that for a resistive load and 550 micro-farads but was very similar to that for a resistive load and 240 micro-farads. See Fig. 43.

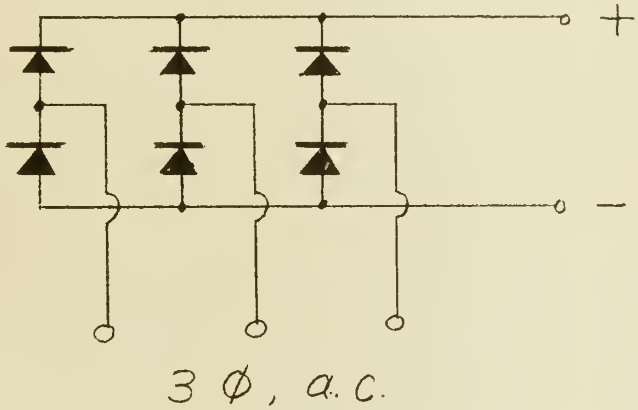


Fig. 10. Three phase bridge circuit.

The wave form of voltage across the inductive load with 60 cycles per second is different from that with a resistive load. See Figs. 62 and 57. The regulation is poorer and the ripple factor figher for the inductive load. For 400 cycles per second the waveforms are very similar for inductive and resistive loads. See Figs. 63 and 58.

Comparison of Figs. 64(a) and 59(a) shows a considerable variation in the rectifier current waveform for 60 cycles per using an inductive and resistive load respectively. Comparison

of Figs. 64(b) and 60(a) shows no variation in the rectifier current waveform for 400 cycles per second using either an inductive or resistive load.

Rectifiers 2 and 3 were used to form a full wave rectifier circuit with a resistive load an no filter. Figs. 65 and 66 are the voltage waveforms across the load for 60 and 400 cycles per second respectively. The waveforms for 60 cycles per second are normal except at full load there is a short dead spot when neither recitier is conducting. This dead spot is more pronounced for the 400 cycle per second waveform, also this waveform is a distorted sine wave.

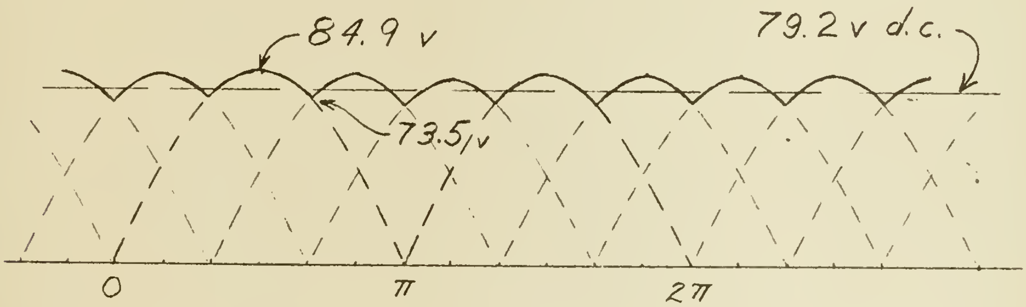


Fig. 11. Output waveform of a three phase bridge rectifier.

The author realizes that in a practical installation the alternating-current source is normally three phase and a three phase bridge circuit as in Fig. 10 would be used. In such a circuit each rectifier conducts for only 120 degrees out of each cycle and rests for 240 degrees; consequently, the load current through each rectifier can be increased by 50 percent.

Such a circuit does not normally employ a filter capacitor. With an effective input voltage of 60 volts, giving a peak voltage of 84.9 volts, an output direct-current voltage of 79.2 volts is theoretically possible. See Fig. 11. The ripple factor for this wave is 0.042 without a filter.

CHAPTER IV

EFFICIENCY

1. Without filter.

The efficiency of a full wave rectifier system is defined (5) as

$$\eta = \frac{P_{d.c.}\ (out)}{P_{a.c.}\ (in)} = 2\left(\frac{2}{\pi}\right)^2 \times \frac{1}{1+\frac{R_o}{R}} = \frac{81.2}{1+\frac{R_o}{R}},$$

where R_o is the internal resistance of the rectifier in the forward direction, assumed to be linear, and R is the resistance of the load. This efficiency is known as the "conversion efficiency", the ability to convert alternating-current power into direct-current power. The efficiency approaches a theoretical maximum of 81.2 percent for this idealized full-wave rectifier as R becomes large compared with R_o. The factor

$$\frac{1}{1+\frac{R_o}{R}}$$

accounts for the heat lost in the rectifier element; it is the fraction of the input power delivered to the load. Only a portion of the power delivered to the load is direct-current power. The remainder is dissipated as heat associated with the alternating components of the load current. The factor

$$2\left(\frac{2}{\pi}\right)^2$$

accounts for this loss in the circuit and is the fraction of the power delivered to the load that is converted to direct-current power.

The circuit used to measure the efficiency of rectifier 1 is shown in Fig. 12. The secondary voltage V_1 was held at

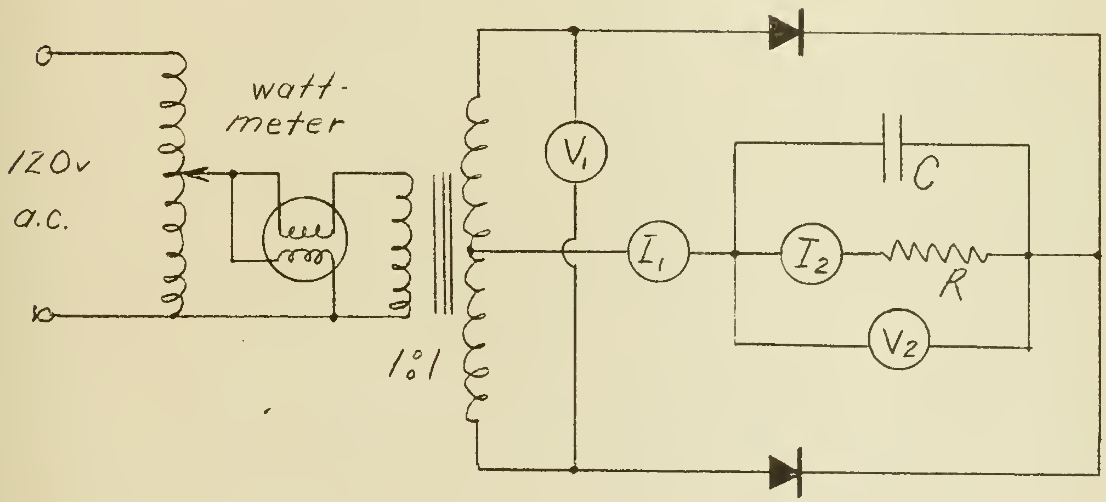


Fig. 12. Circuit used to obtain rectifier efficiency.

120 volts. The wattmeter was placed in the primary circuit for two reasons. First the transformer action reversed one half cycle of the current giving an alternating current instead of a pulsating direct current. Second the inductance of the transformer tended to smooth out the narrow pulses of current which occurred when a filter capacitor was in the circuit. Both effects reduced the higher harmonics of current and gave more accurate readings with the wattmeter. This circuit arrangement required the determination of the transform-

er losses in order to obtain the true input power on the secondary side. Fig. 45 shows these losses as a function of output alternating current.

The no-filter efficiency curves for 60 and 400 cycles per second are shown in Fig. 46. The full load efficiency is approximately 77 percent and the efficiency curve is flat over most of the operating range.

2. With filter.

A 240 micro-farad filter capacitor was applied across the load. The capacitor reduces the alternating components of load current and consequently the losses associated with them. The better the filtering action, the higher the efficiency should be. This is borne out in Fig. 46. With 60 cycles per second the filter is effective only at low values of load current and thus the efficiency at these points is higher. At full load where the ripple factor is still 0.483 the efficiency is 77.5 percent as compared to about 77 percent with no filter. For 400 cycles per second the filter is effective at full load where the ripple factor is 0.098 and the efficiency as shown by Fig. 46 is approximately 91 percent.

CHAPTER V

CONCLUSIONS

1. Volt-ampere characteristics.

Fig. 34 indicates that there is little change in the forward volt-ampere characteristics when going from 60 to 400 cycles per second. The voltage drop for a given load current is slightly greater for 400 cycles per second than for 60 cycles per second. It was possible that this change could be caused by some type of aging in the rectifier since the 60 cycle per second tests were made several days prior to the 400 cycle per second tests. Consequently a new forward volt-ampere curve for 60 cycles per second was obtained and it lay identically on top of the first. Thus the change between the 60 and 400 cycle per second curves can be attributed only to frequency.

In the reverse direction the 60 and 400 cycle per second curves were nearly identical, with the 400 cycle per second curve having a slightly greater leakage current than the 60 cycle per second curve for a given inverse voltage.

In both the forward and reverse directions rectifier 1 is a better rectifier at 60 cycles per second than at 400 cycles per second; however, the difference is probably insignificant and it is concluded that the rectifier would operate equally well at either frequency.

2. Effect of temperature.

The effect of temperature is nearly the same for both 60 and 400 cycles per second. In the forward direction the voltage drop across the rectifier decreases with an increase in temperature. This decrease is perceptibly more rapid for 400 than for 60 cycles per second. This implies a decrease in resistance or an increase in current with an increase in temperature and thus more losses in the rectifier.

In the reverse direction an increase in temperature causes an increase in reverse current. This increase becomes very rapid at high temperatures with the result that reverse I^2R losses increase greatly with temperature. The difference between the effect of temperature on operation at 60 and 400 cycles per second in the reverse direction is negligible.

The steady state temperature of the rectifier with no cooling fan averaged $2\frac{1}{2}$ degrees higher at 60 cycles per second than at 400 cycles per second. This was 12 percent of the total temperature rise. It is concluded that rectifier 1 would operate cooler at 400 cycles per second than at 60 cycles per second but that the difference is insignificant.

3. Resistance.

It is obvious that since the characteristic curves for 60 and 400 cycles per second are so similar, the resistance curves would likewise be very similar. What ever value of resistance is chosen to represent the rectifier at 60 cycles per second could adequately represent it at 400 cycles per

second.

4. Regulation.

The regulation without a filter capacitor was very similar for both 60 and 400 cycles per second and it can be concluded that neither has an advantage. However, when a filter capacitor is added the 400 cycle per second power has a decided advantage, which would be true for any type of rectifier. The operation at 400 cycles per second can give a specified regulation or ripple factor with a much smaller capacitor than can 60 cycles per second. As the filter capacitor is increased, the peak current through the rectifier increases. For the rectifier circuit tested the peak currents nearly doubled. In this case there appeared to be no adverse effects on the rectifier. It must be remembered that increasing the peak current increases the I^2R losses in the rectifier thus raising the rectifier temperature. Table XXVI shows that adding 550 micro-farads of capacitance raised the temperature 2.3 degrees for 60 cycles per second and 3.5 degrees for 400 cycles per second. Raising the temperature of the rectifier allows the reverse current to increase greatly thus there is an upper limit to the forward peak current.

It was noted that the waveforms at 400 cycles per second were the same for both a resistive and inductive load; however, for 60 cycles per second the inductive load introduced considerable distortion.

It is concluded that the rectifier operation is as good

or better with 400 cycles per second than with 60 cycles per second when only regulation is the governing factor.

5. Efficiency.

It was shown in Fig. 46 that the efficiency curves for 60 and 400 cycles per second were very similar if no filter capacitor was used. With the addition of a specified filter capacitor the 400 cycle per second operation had a decided advantage. Therefore it is concluded that the rectifier operation is as good or better with 400 cycles per second than with 60 cycles per second when only efficiency is the governing factor.

6. Summary.

In no case investigated was 400 cycle per second power detrimental to the operation of the rectifier. The effects of time and temperature were the same as for 60 cycles per second. The volt-ampere characteristics were the same as for 60 cycles per second. The regulation and efficiency were the same as for 60 cycles per second while the addition of a filter capacitor across the output made the regulation and efficiency much better than for 60 cycles per second. Such a filter capacitor would normally only be used for single phase operation.

In conclusion the author sees no reason why germanium power rectifiers as now manufactured for 60 cycle per second industrial power could not be effectively utilized for 400 cycle per second aircraft power. The author believes that

further studies should be made before a final approval can be given. These studies could include: the measurement of rectifier self capacitance; the effect of extremely cold temperatures; the transient effects of suddenly applied or removed loads.

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APPENDIX A

GRAPHICAL RESULTS

The following pages contain the curves and graphs which resulted from the data taken. Each curve is a graphical representation of one or more tables in Appendix C.

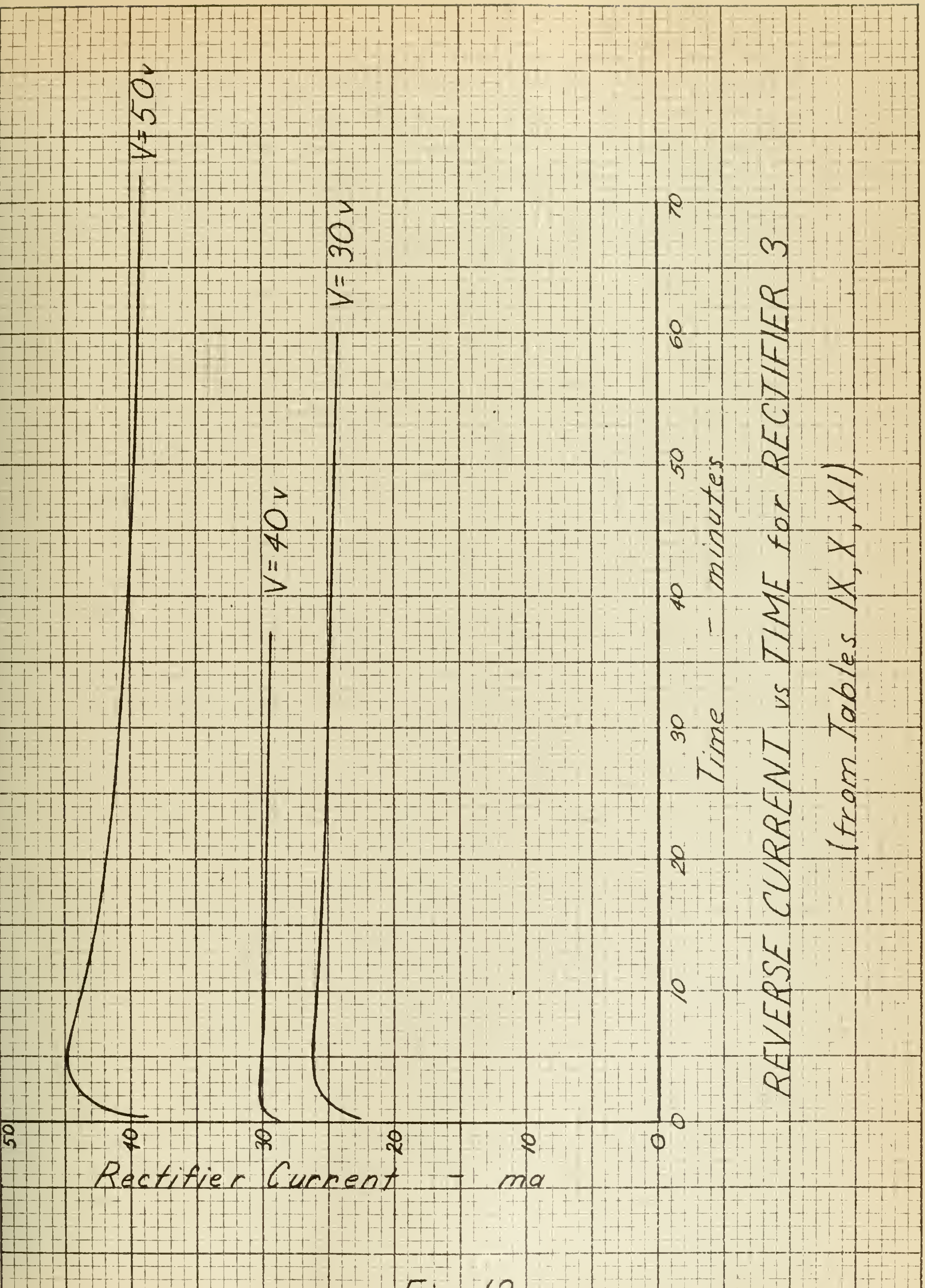
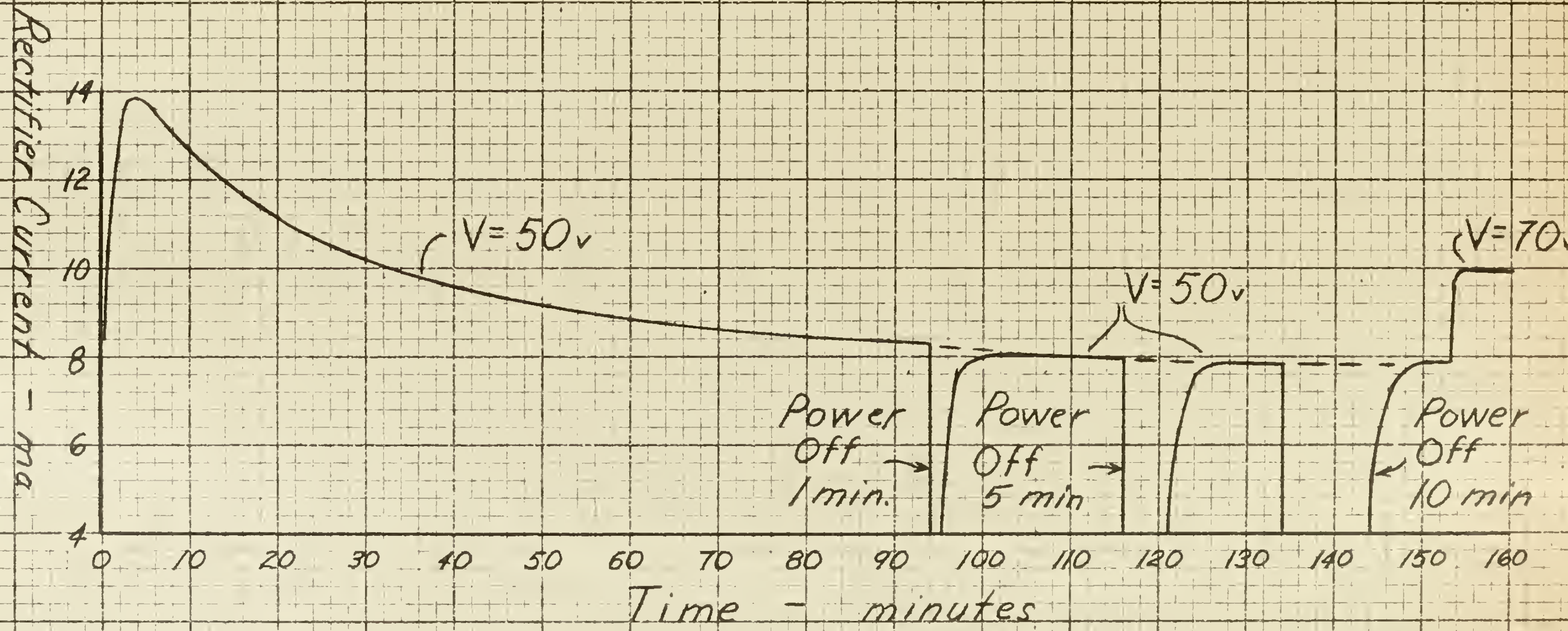

V=50v
V=40v
V=30v
0
10
20
30
40
50
60
70
Time - minutes
Rectifier Current - ma
REVERSE CURRENT vs TIME for RECTIFIER 3
(from Tables IX, X, XI)

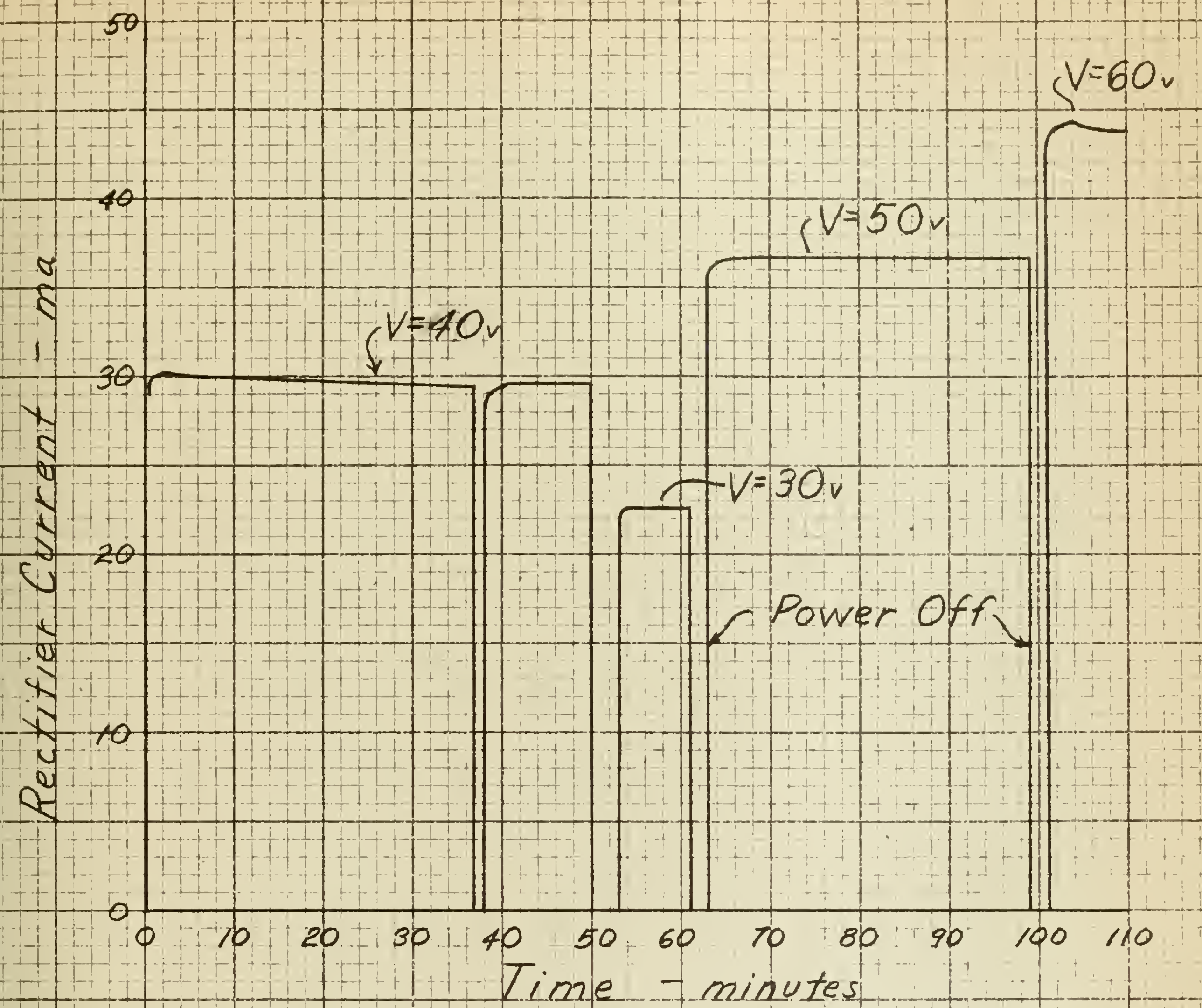
Fig. 13.



EFFECT of POWER SHUT OFF and VOLTAGE CHANGE on REVERSE CURRENT of RECTIFIER 2

(from Table XII)

Fig. 14.



EFFECT of Power SHUT OFF and VOLTAGE CHANGE on REVERSE CURRENT of RECTIFIER 3 (from Table XI)

Fig. 15.

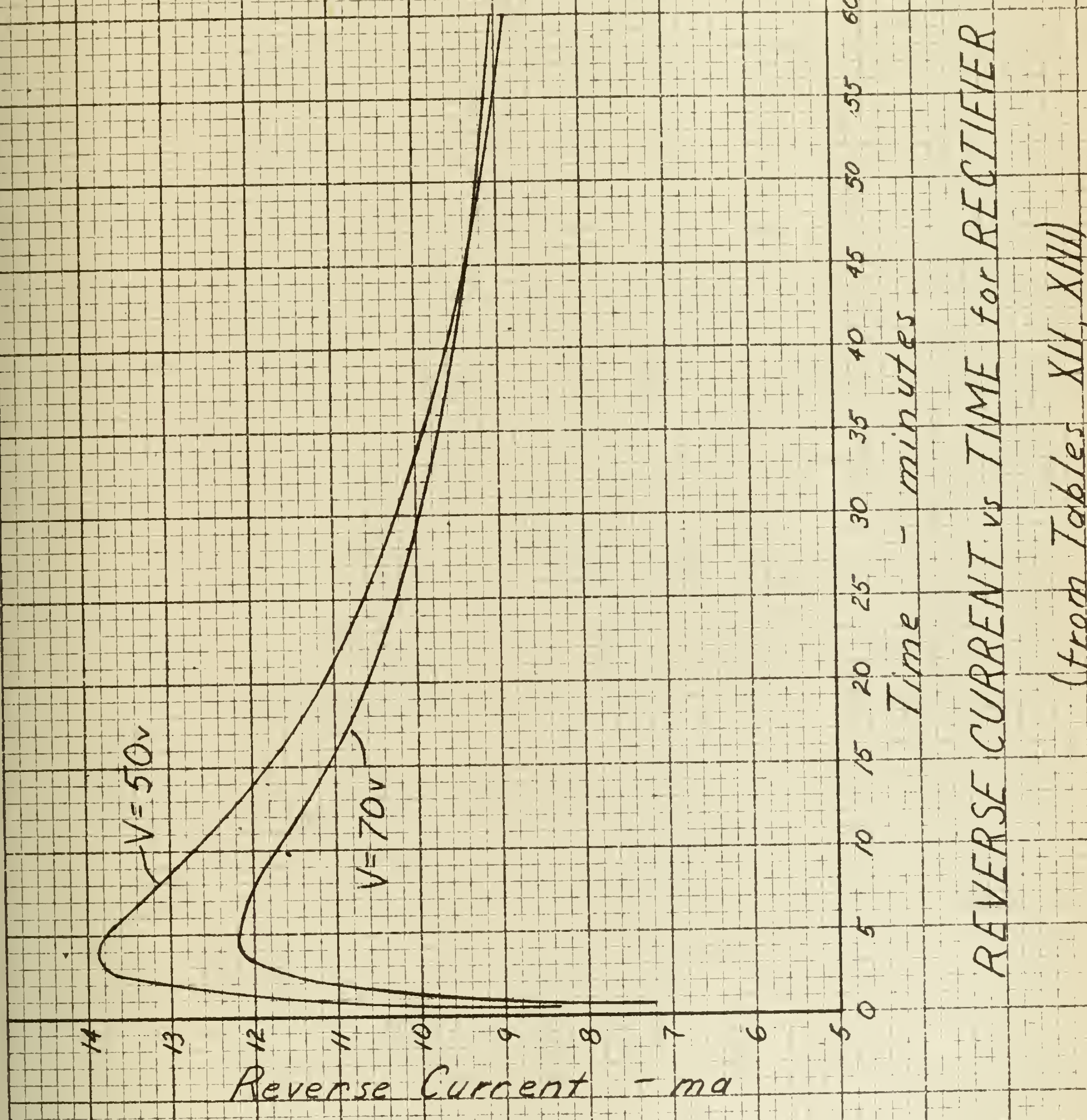
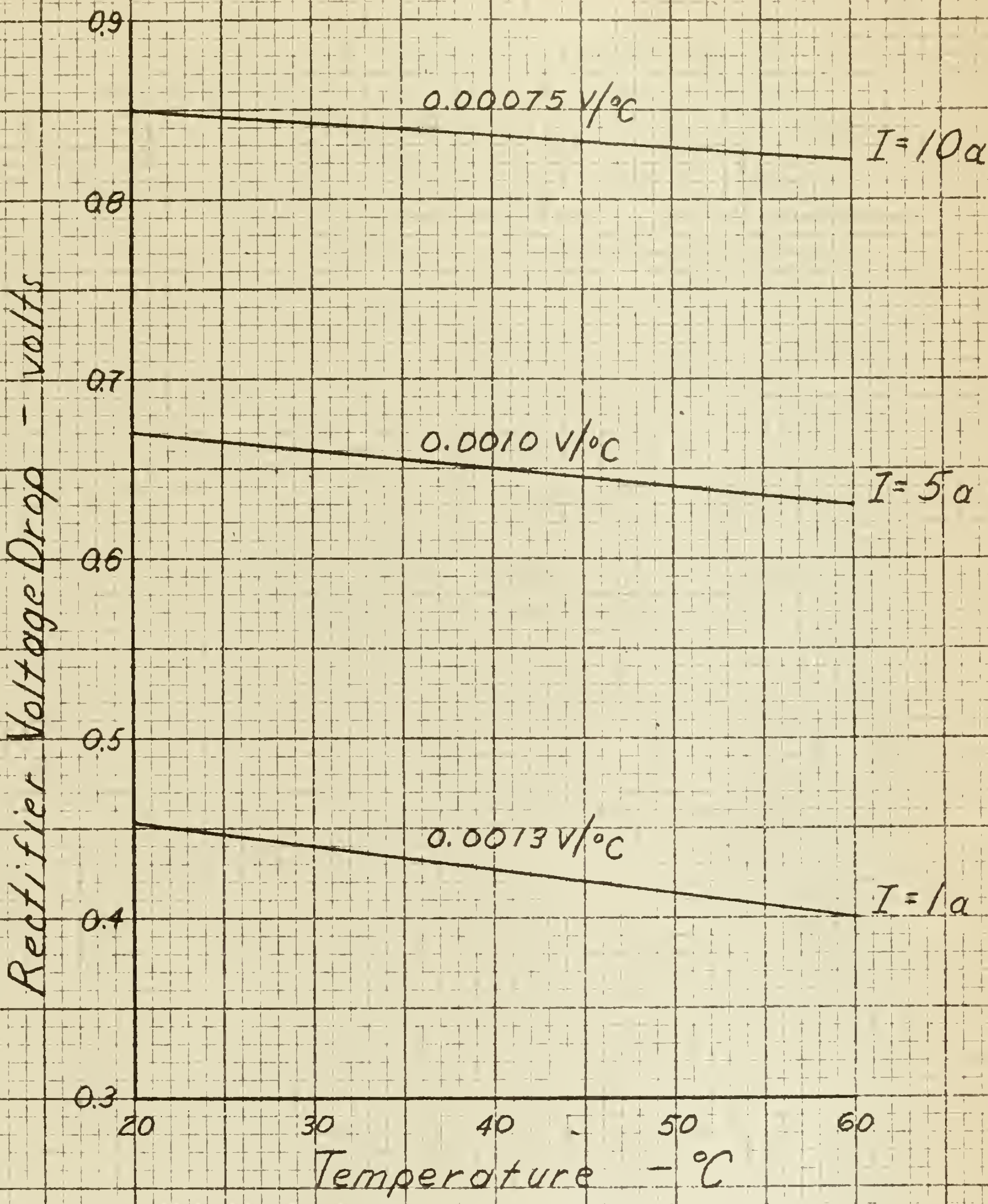
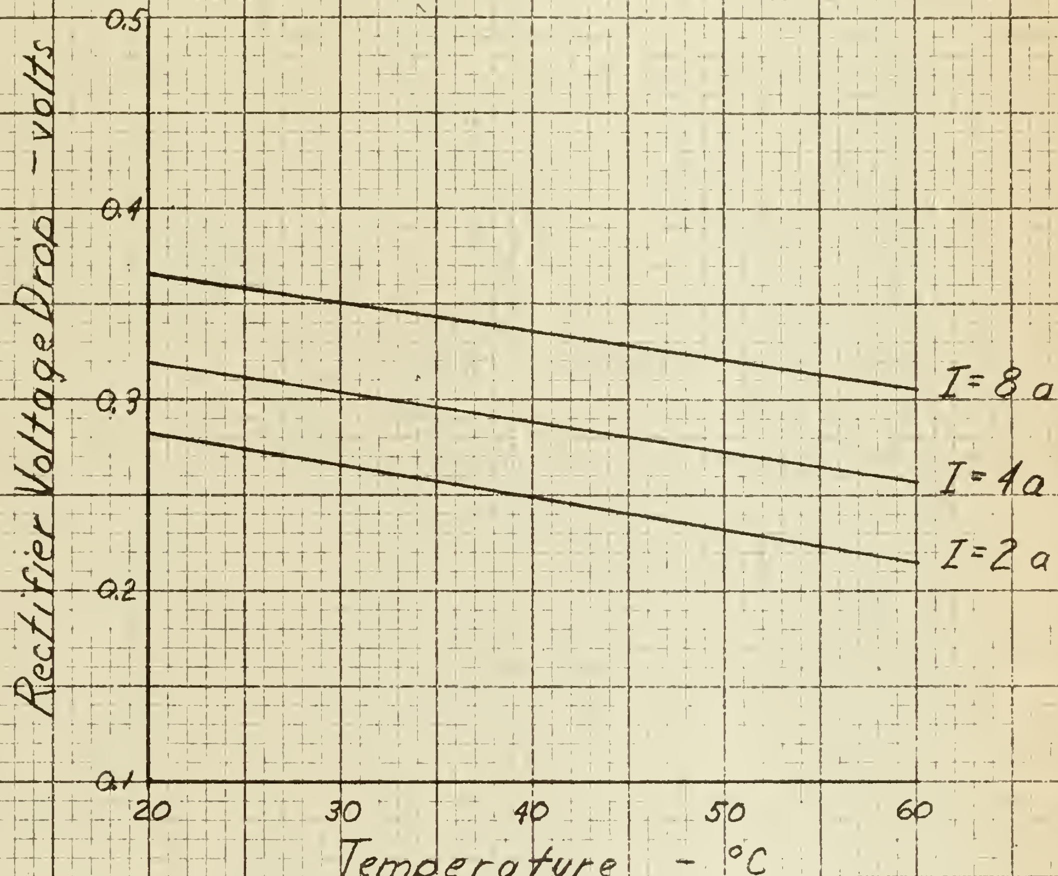

REVERSE CURRENT vs TIME for RECTIFYER 2
(from Tables XIV, XIII)
V=50v
V=70v
Time - minutes
0 5 10 15 20 25 30 35 40 45 50 55 60
Reverse Current - ma
14 13 12 11 10 9 8 7 6 5

Fig. 16.



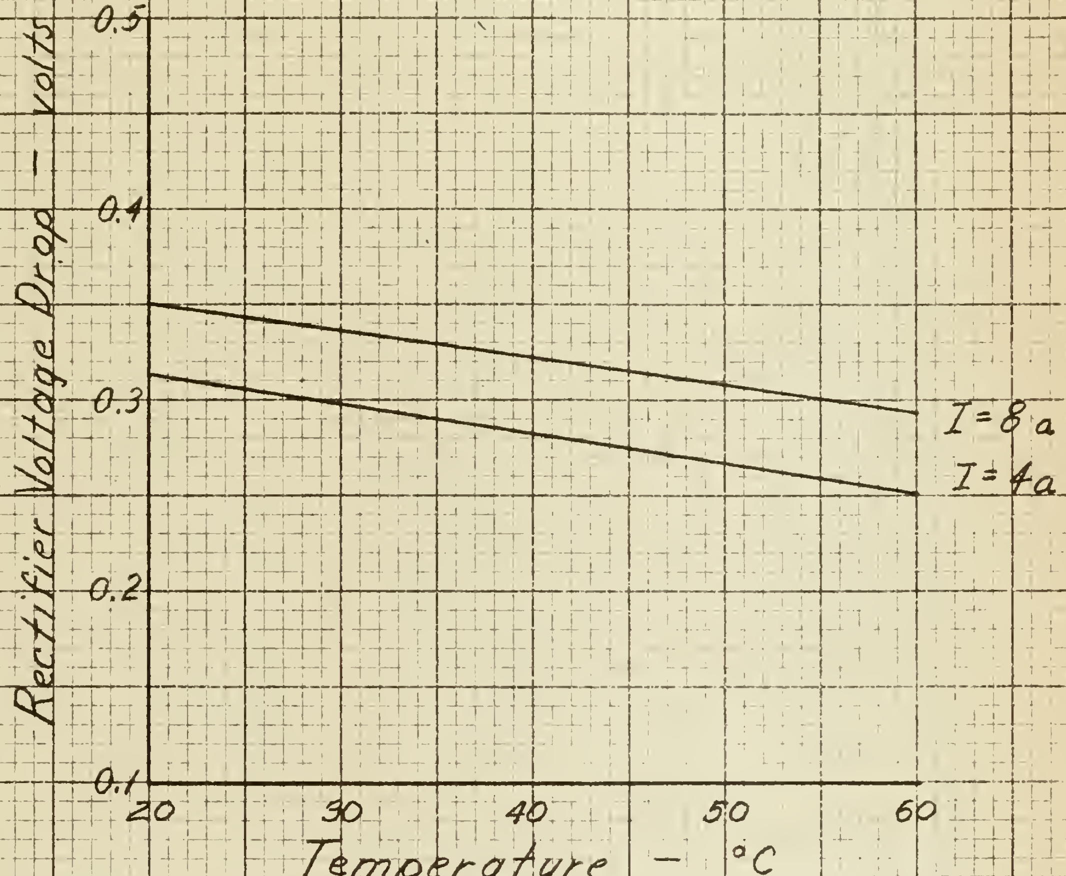
EFFECT of TEMPERATURE on FORWARD D.C. VOLTAGE DROP of RECTIFIER 1
(from Table XIV)

Fig. 17.



EFFECT of TEMPERATURE on FORWARD D.C. VOLTAGE DROP of RECTIFIER 2 (from Table XV)

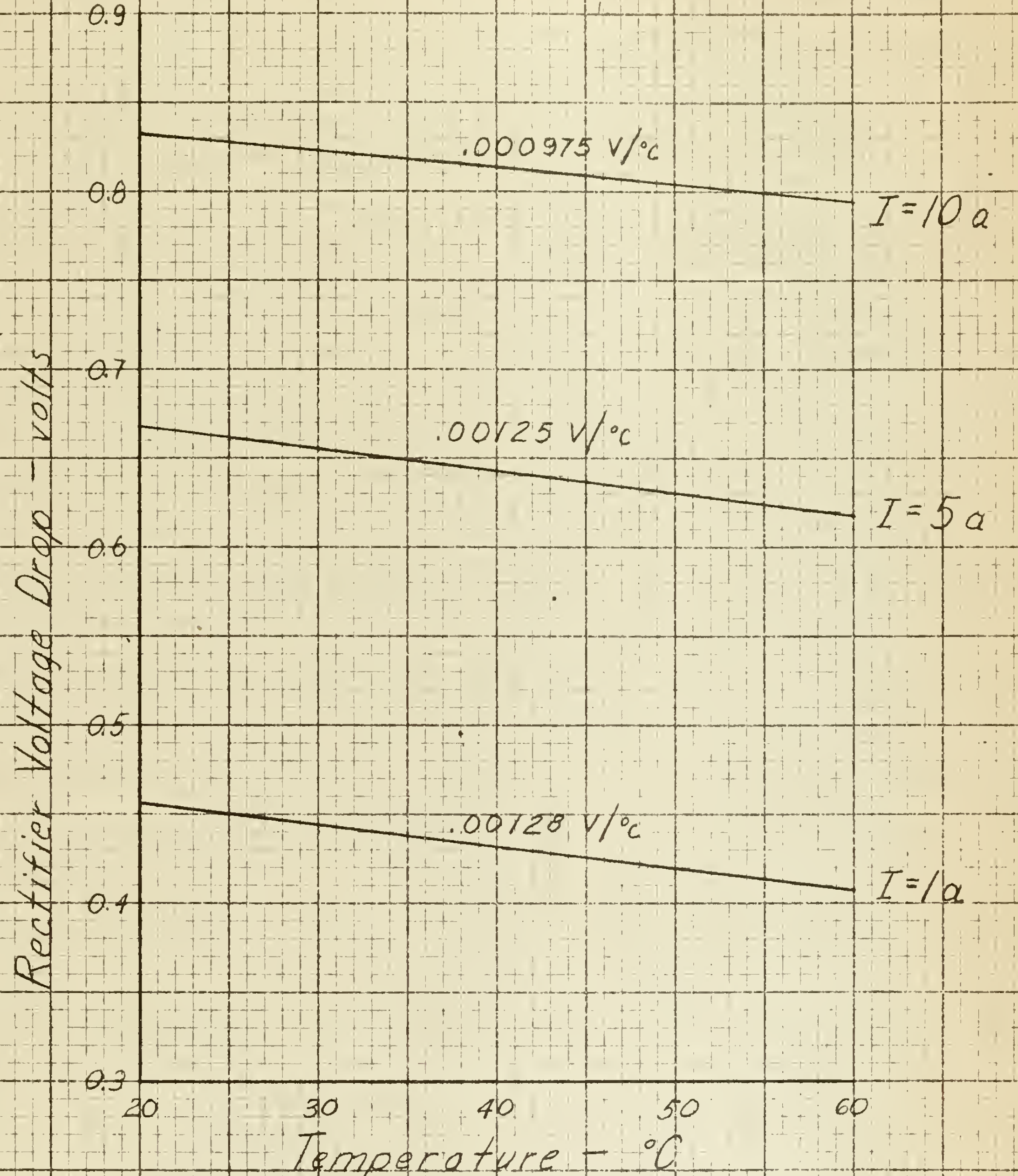
Fig. 18.



EFFECT of TEMPERATURE on FORWARD D.C. VOLTAGE DROP of RECTIFIER 3

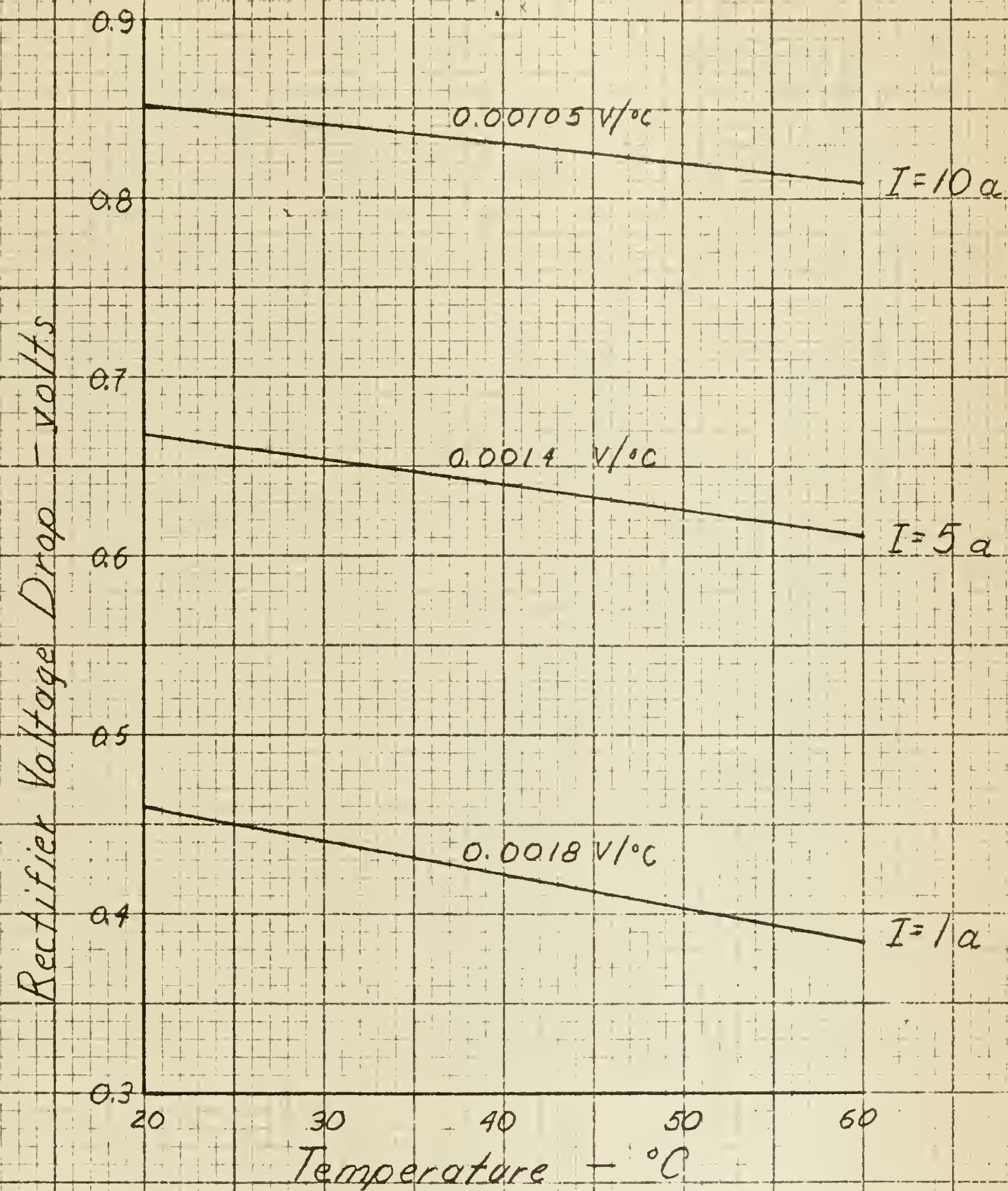
(from Table XVI)

Fig. 19.



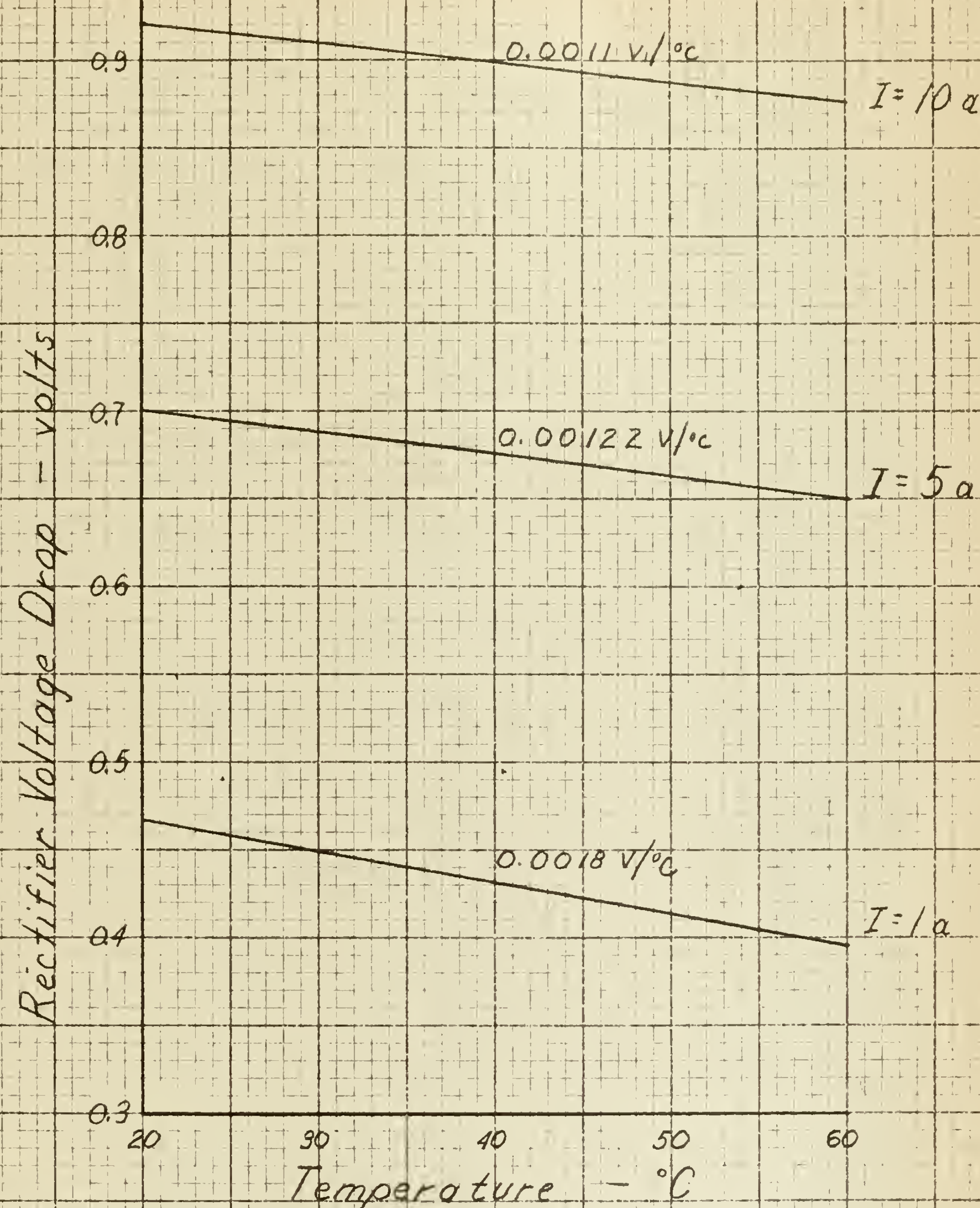
EFFECT of TEMPERATURE on FORWARD 60~ VOLTAGE DROP of RECTIFIER 1 (from Table XVII)

Fig. 20.



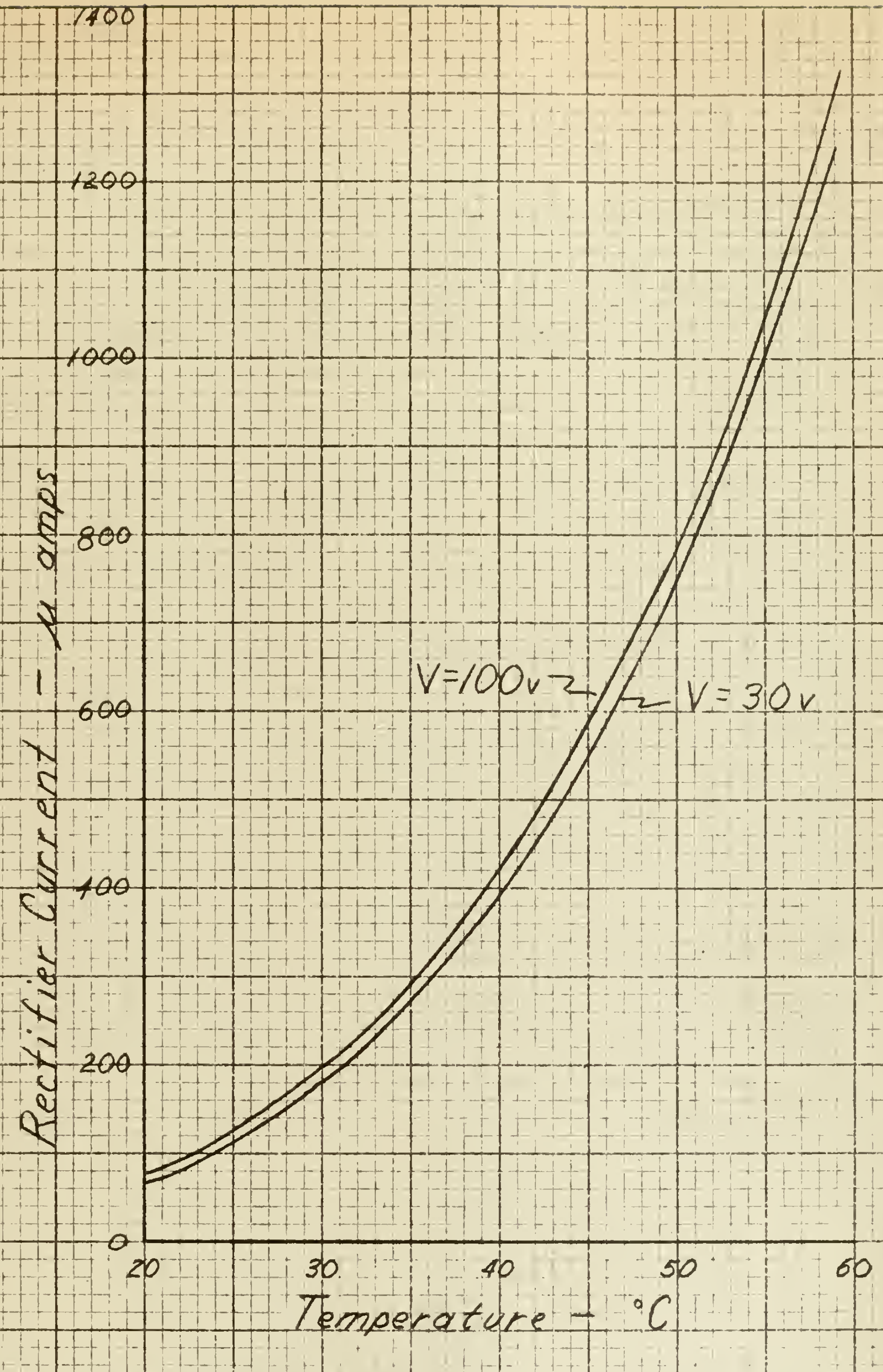
EFFECT of TEMPERATURE on FORWARD 400~ VOLTAGE DROP of RECTIFIER 1 (from Table XVIII)

Fig. 21.



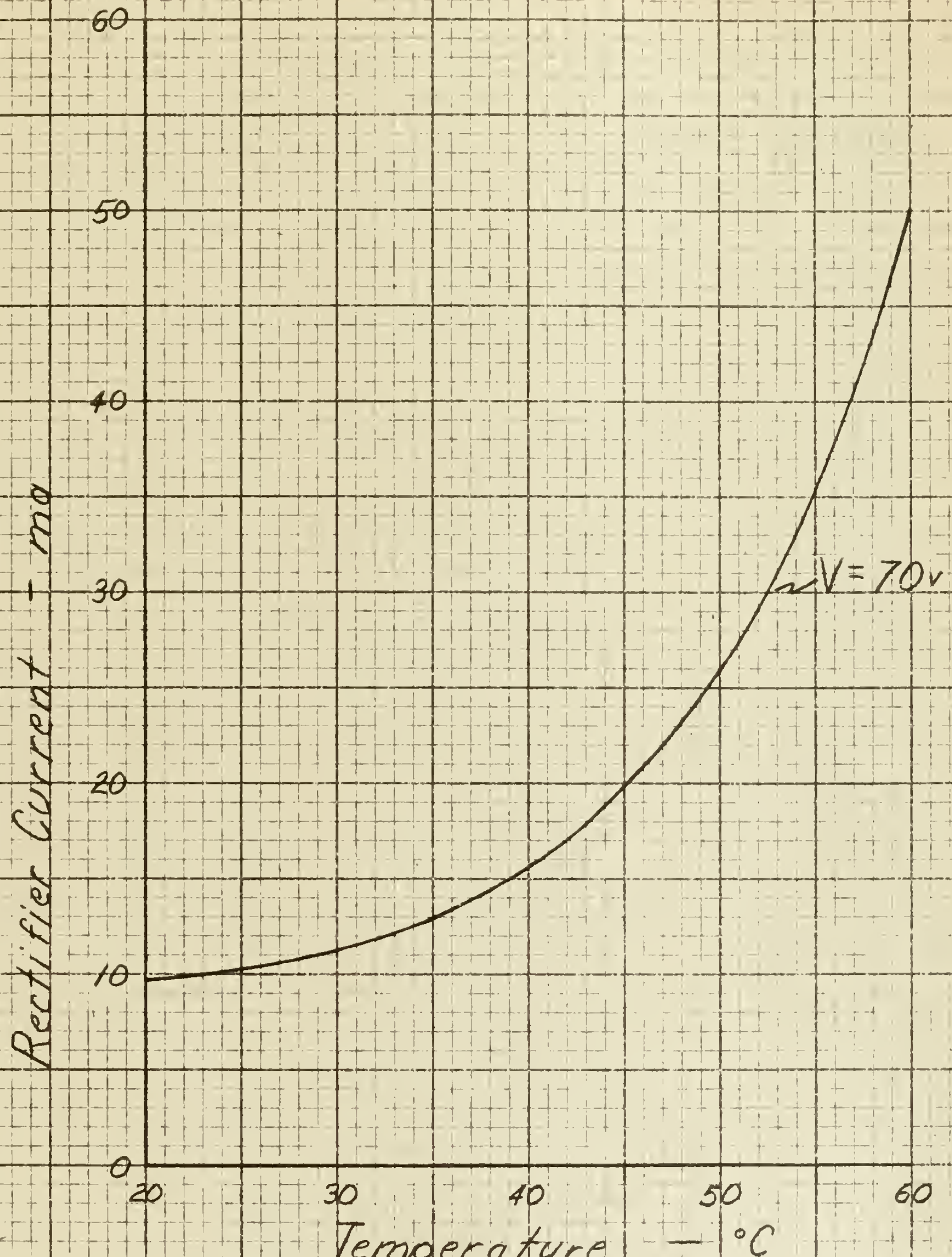
EFFECT of TEMPERATURE on FORWARD 400~ 3 ϕ VOLTAGE DROP of RECTIFIE 1 (from Table XIX)

Fig. 22.



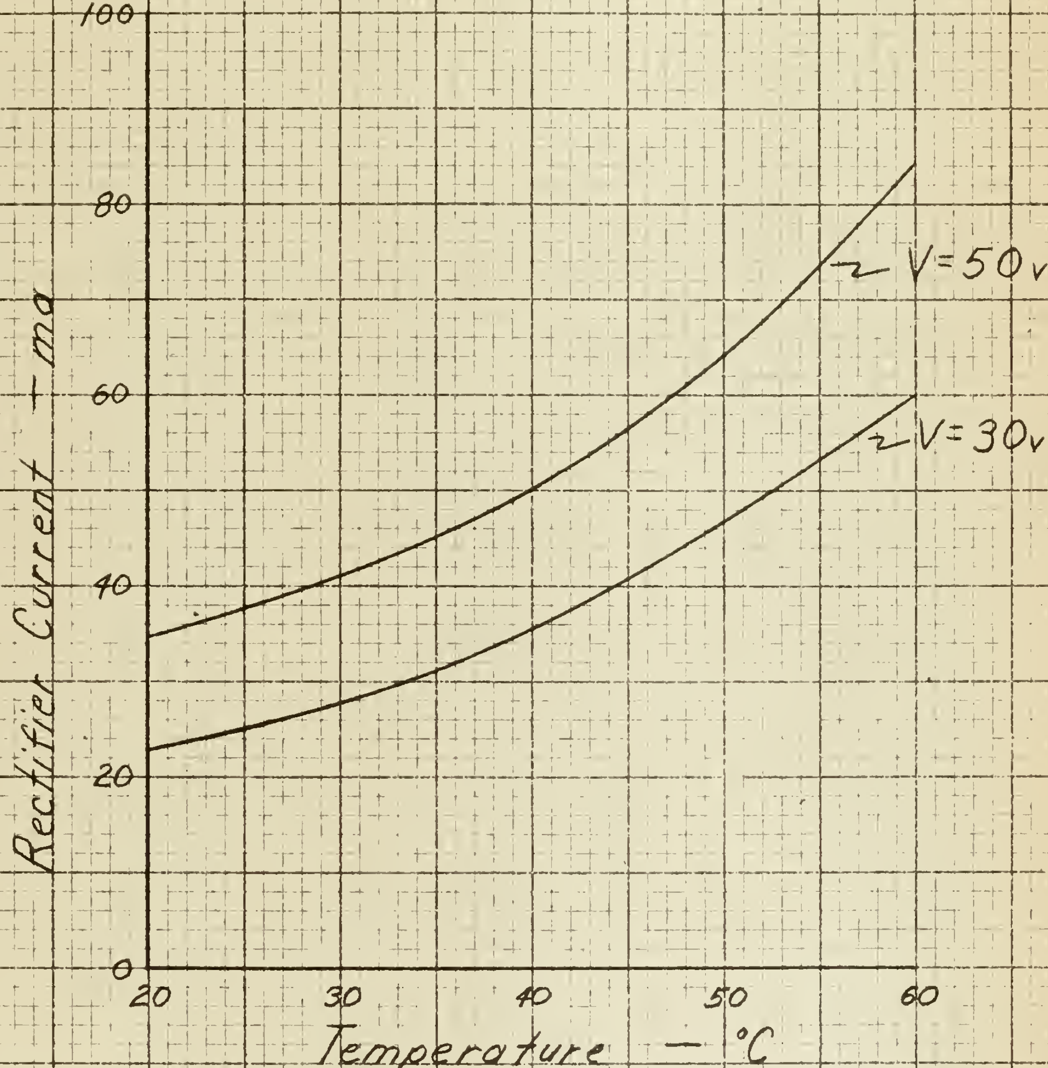
EFFECT of TEMPERATURE on the REVERSE D.C. CURRENT of RECTIFIER 1 (from Table XX)

Fig. 23.



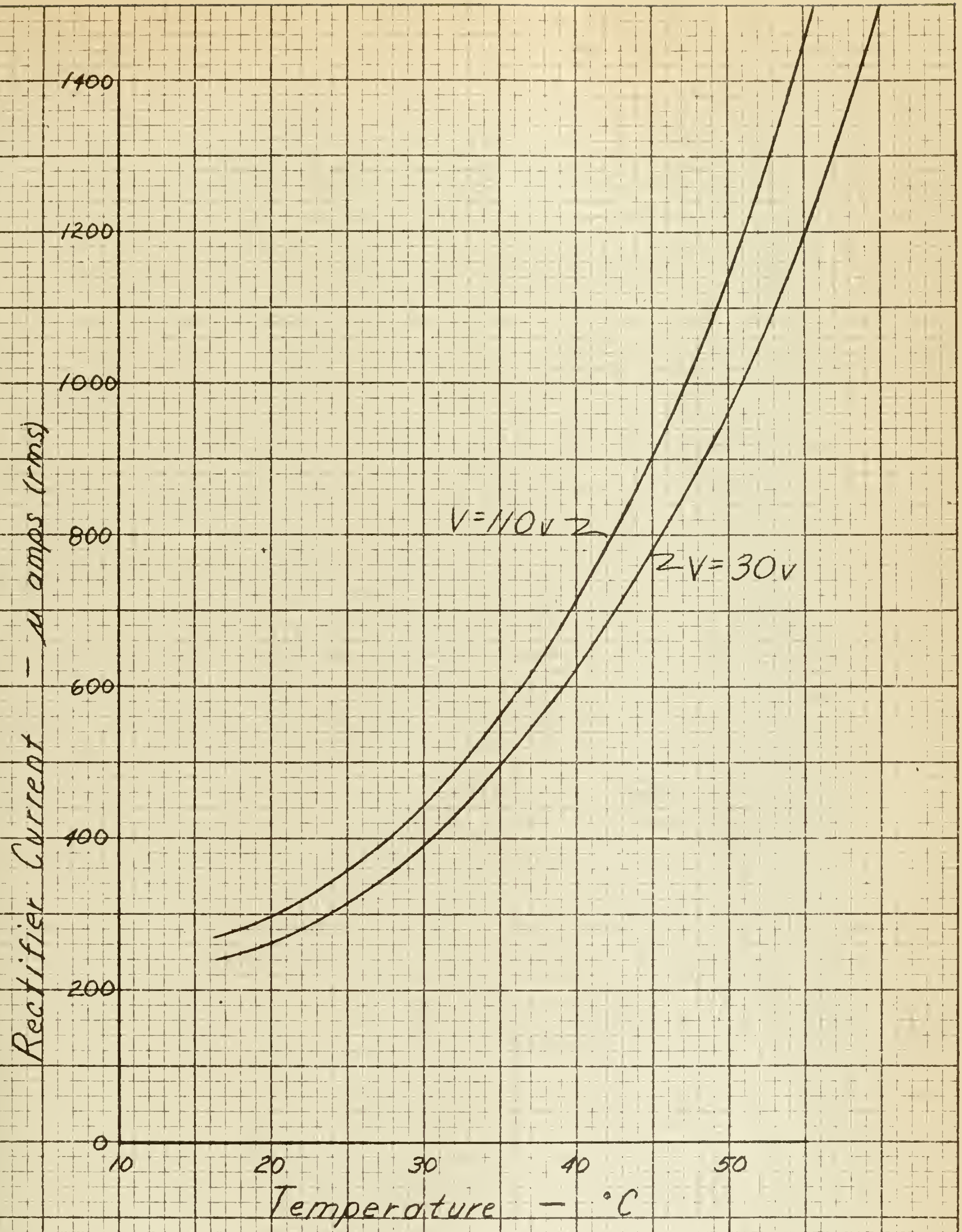
EFFECT of TEMPERATURE on the REVERSE D.C. CURRENT of RECTIFIER 2 (from Table XXI)

Fig. 24.



EFFECT of TEMPERATURE on the REVERSE
D.C. CURRENT of RECTIFIER 3
(from Table XXII)

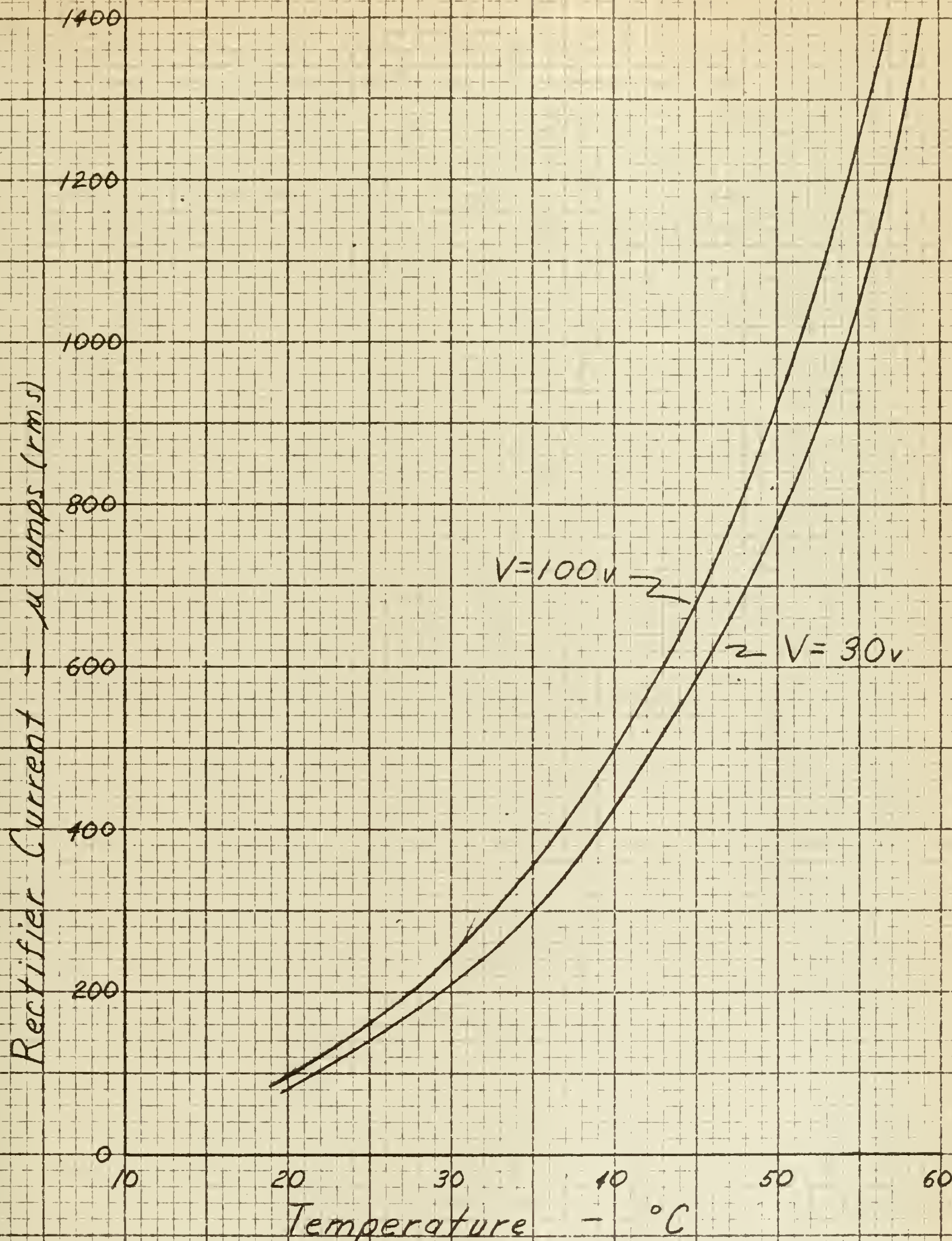
Fig. 25.



EFFECT of TEMPERATURE on the REVERSE 60~ CURRENT of RECTIFIER 1

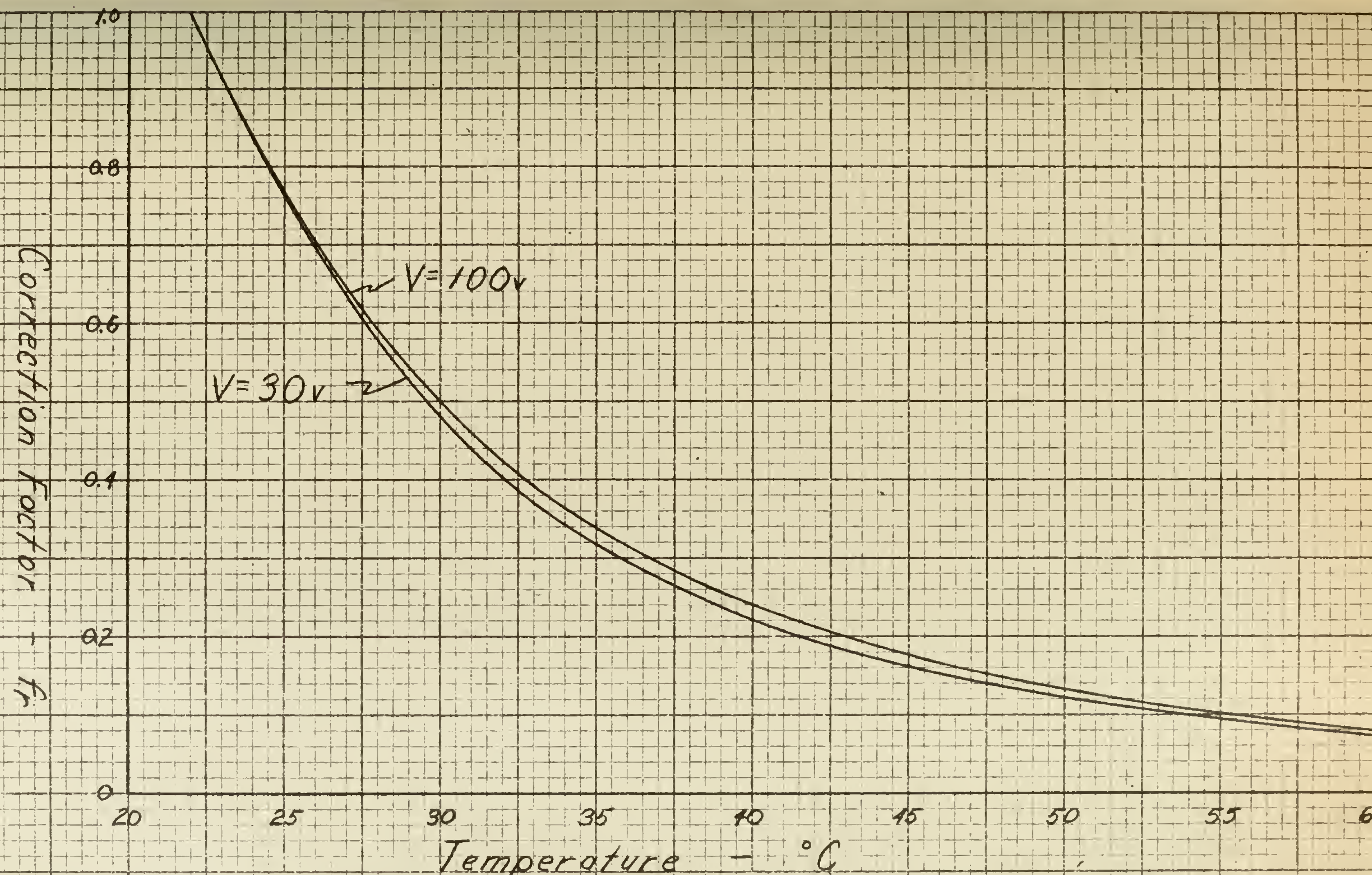
(from Table XXIII)

Fig. 26.



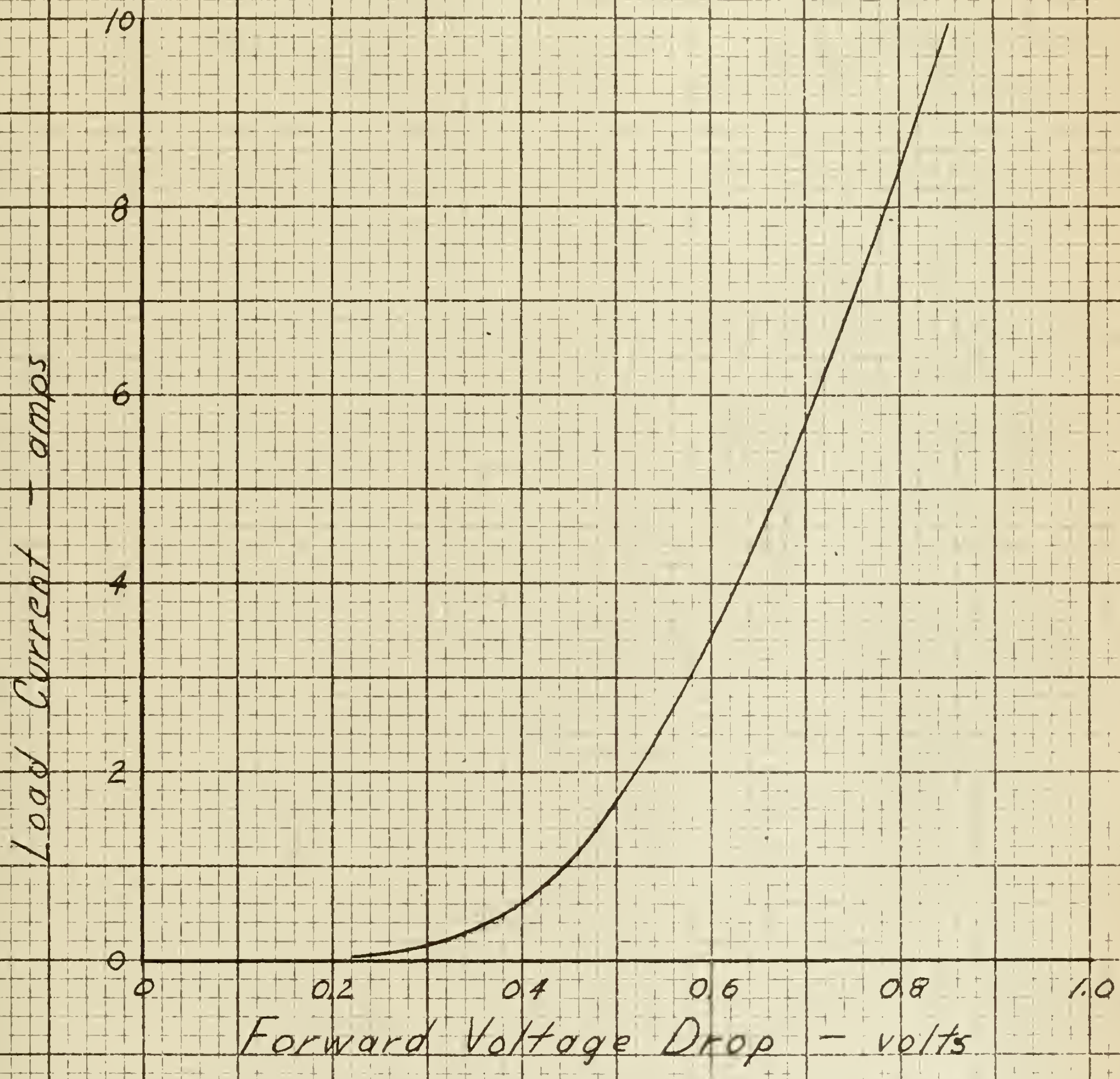
EFFECT of TEMPERATURE on the REVERSE
400~ CURRENT of RECTIFIER 1
(from Table XXIV)

Fig. 27.



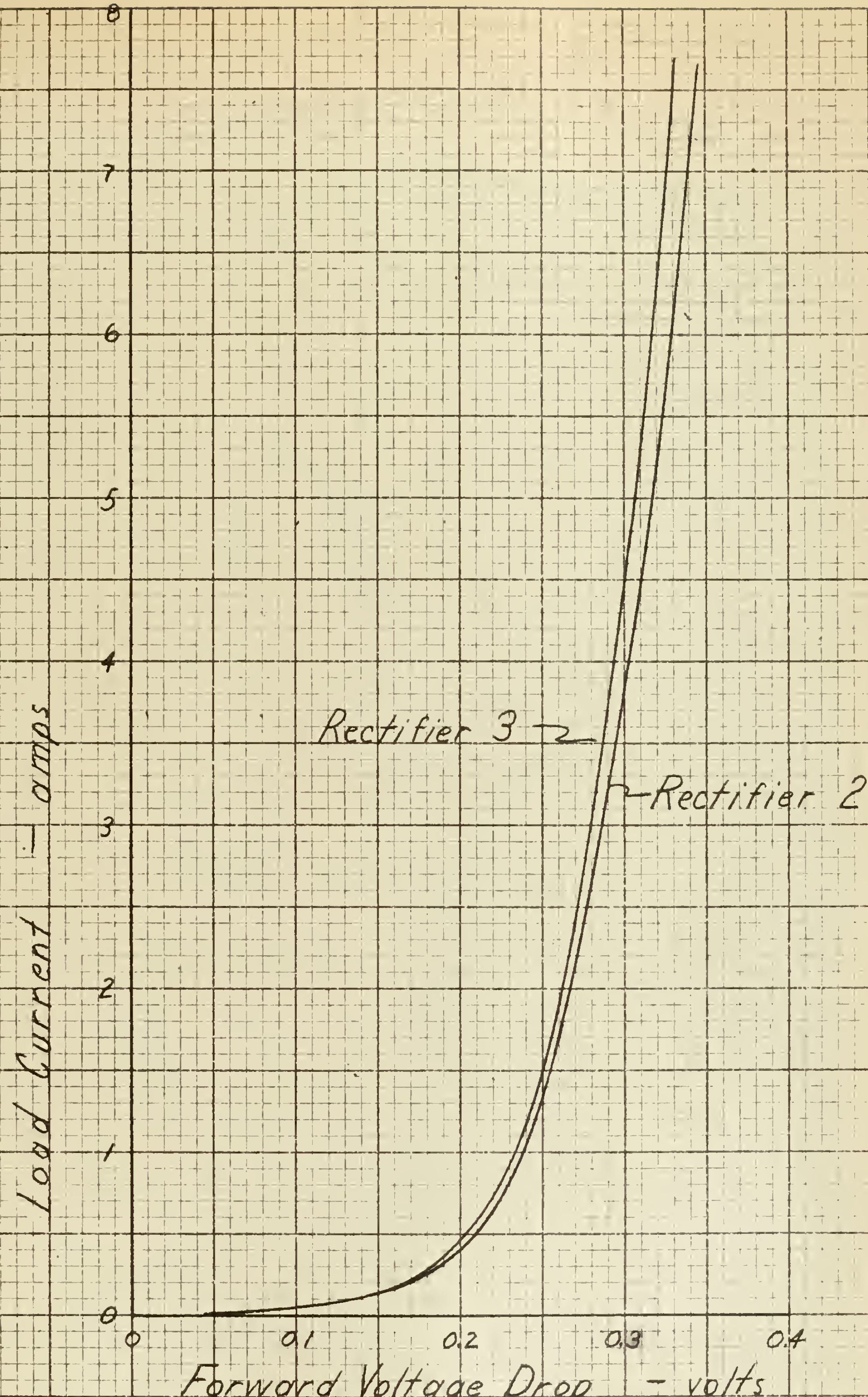
TEMPERATURE CORRECTION FACTOR for D.C. REVERSE CURRENT of RECTIFIER 1; CORRECTED to 22 °C (from Table XXV)

Fig. 28.



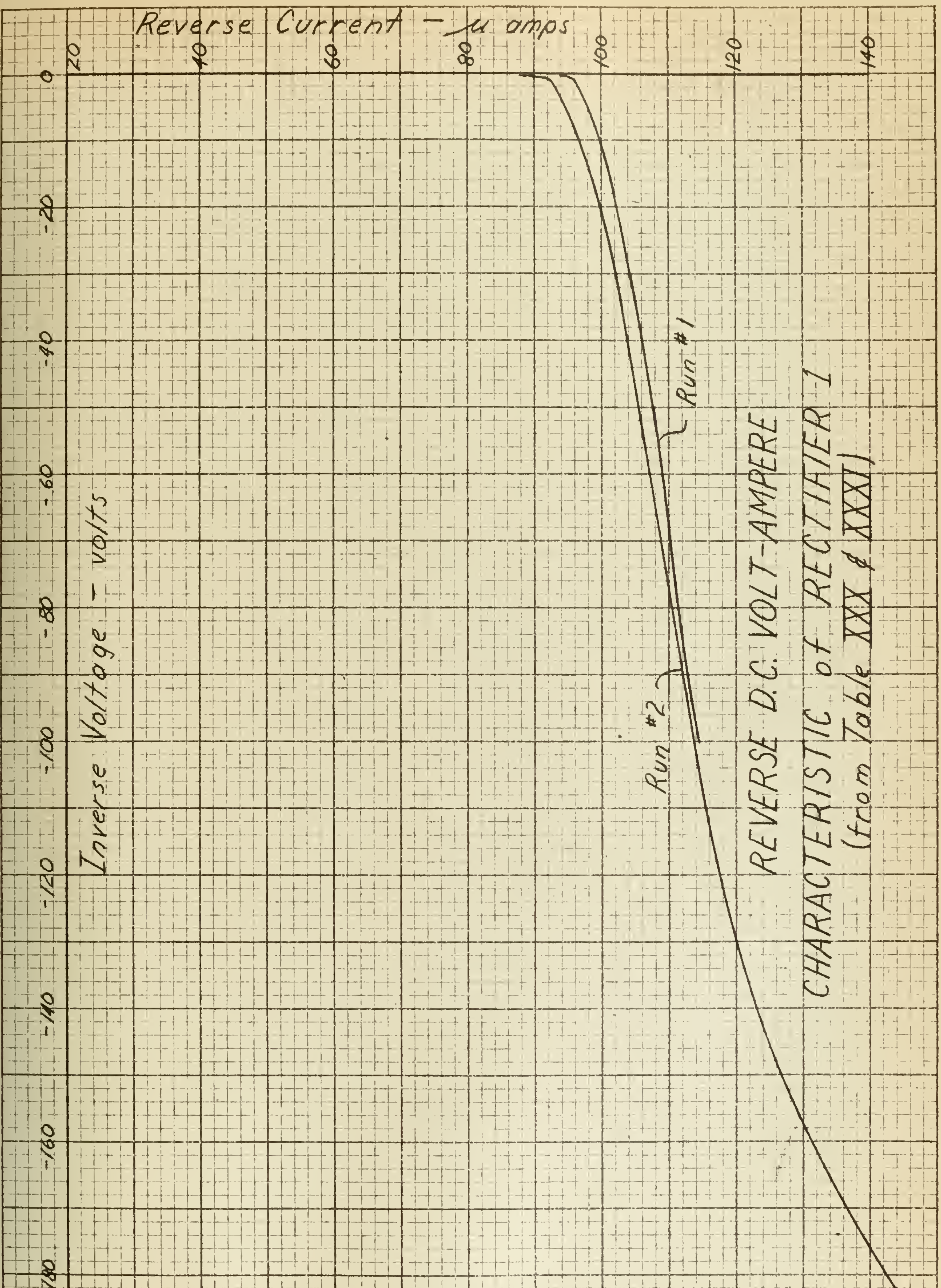
FORWARD D.C. VOLT-AMPERE
CHARACTERISTIC of RECTIFIER 1
(from Table XXVII)

Fig. 29.



FORWARD D.C. VOLT-AMPERE CHARACTERISTICS of RECTIFIERS 2 and 3
(from Tables XXVIII & XXIX)

Fig. 30.



Reverse Current — μ amps
20
40
60
80
100
120
140
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
Inverse Voltage — volts
Run #1
Run #2
REVERSE D.C. VOLT-AMPERE
CHARACTERISTIC of RECTIFIER I
(from Table XXX & XXXI)

Fig. 31.

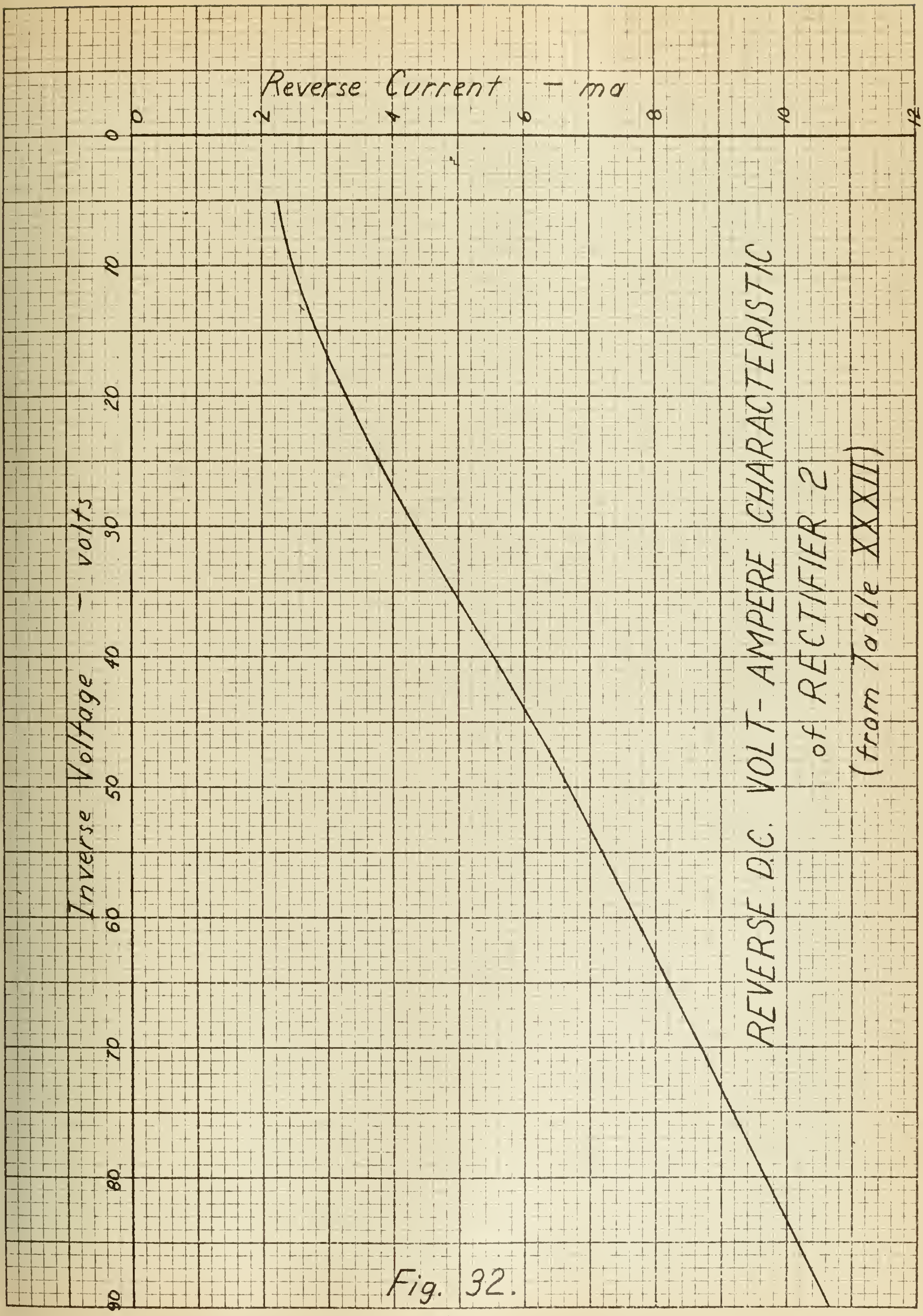

Reverse Current — ma
0
2
4
6
8
10
12
Inverse Voltage — volts
0
10
20
30
40
50
60
70
80
90
REVERSE D.C. VOLT-AMPERE CHARACTERISTIC
of RECTIFIER 2
(from Table XXXII)

Fig. 32.

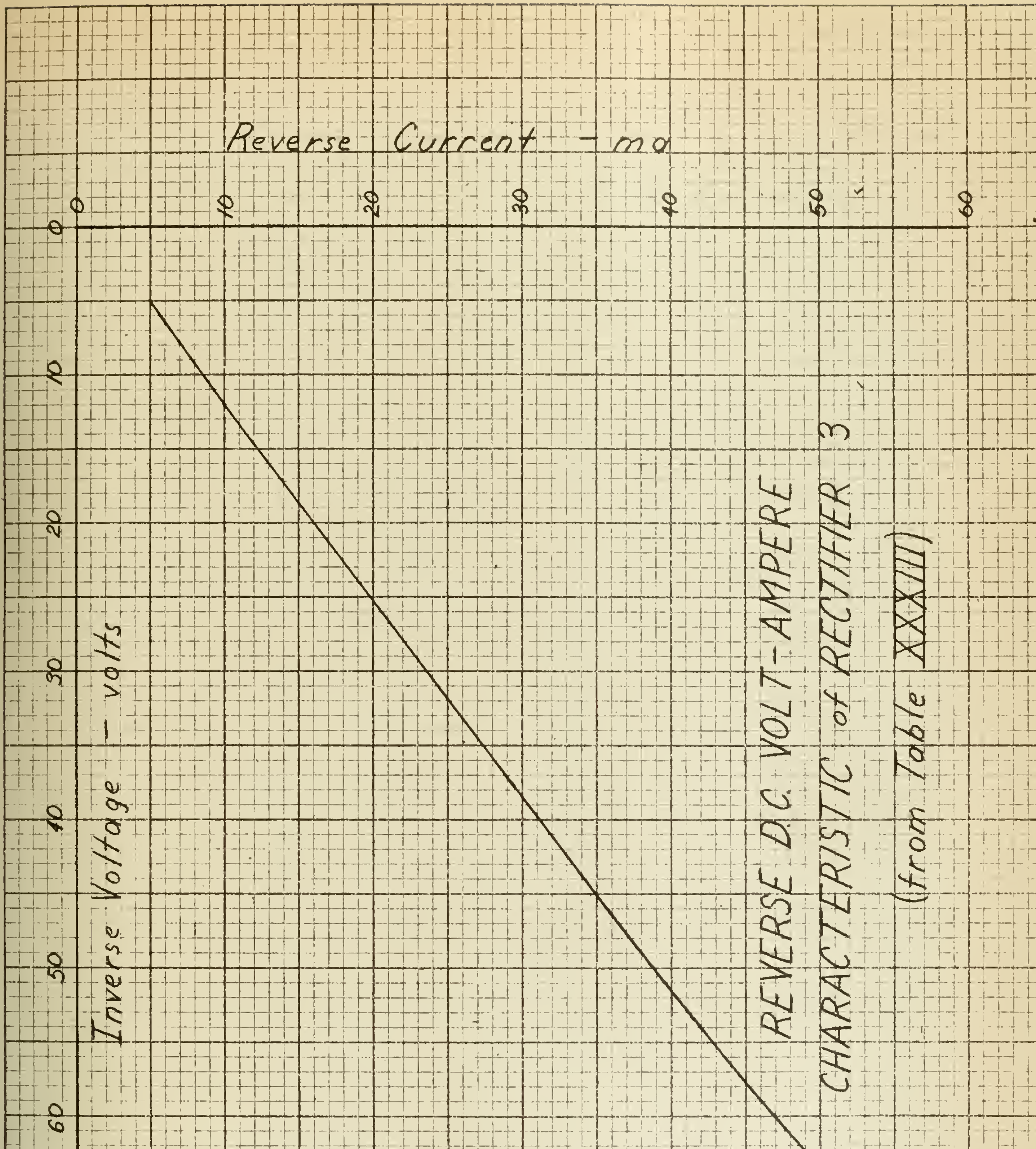
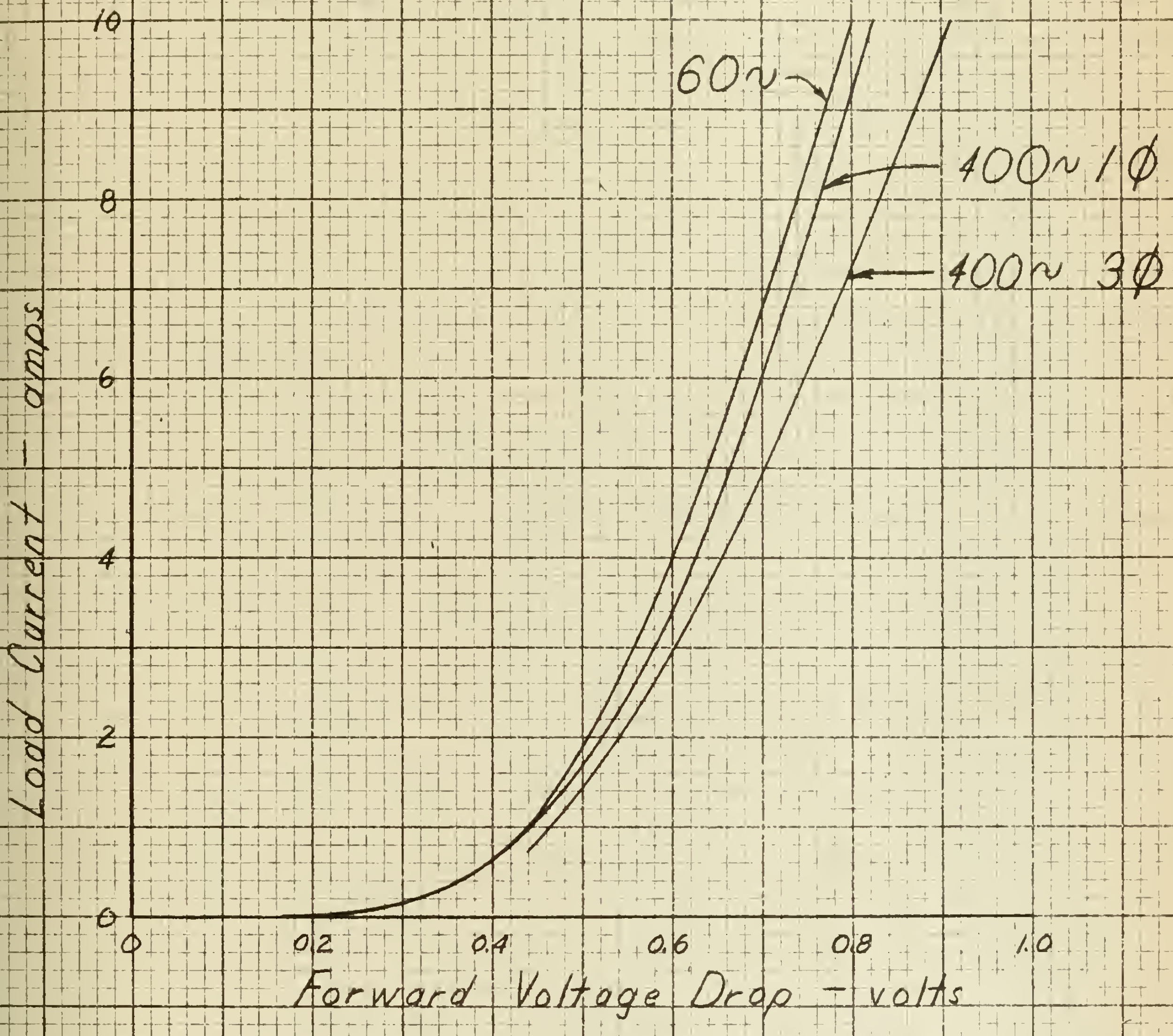
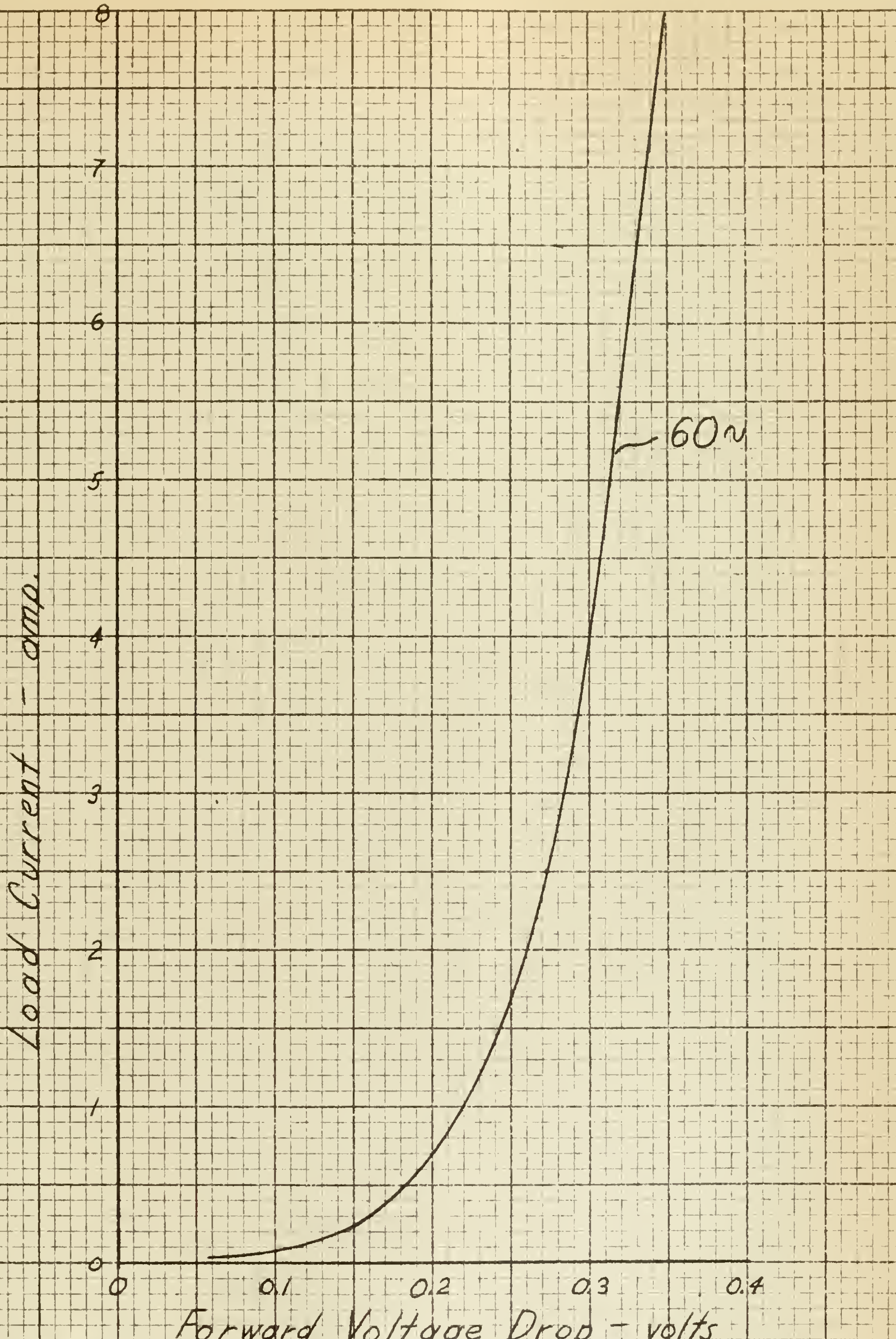

Reverse Current — ma
0
10
20
30
40
50
60
Inverse Voltage — volts
0
10
20
30
40
50
60
70
REVERSE D.C. VOLT-AMPERE
CHARACTERISTIC of RECTIFIER 3
(from Table XXXIII)

Fig. 33.



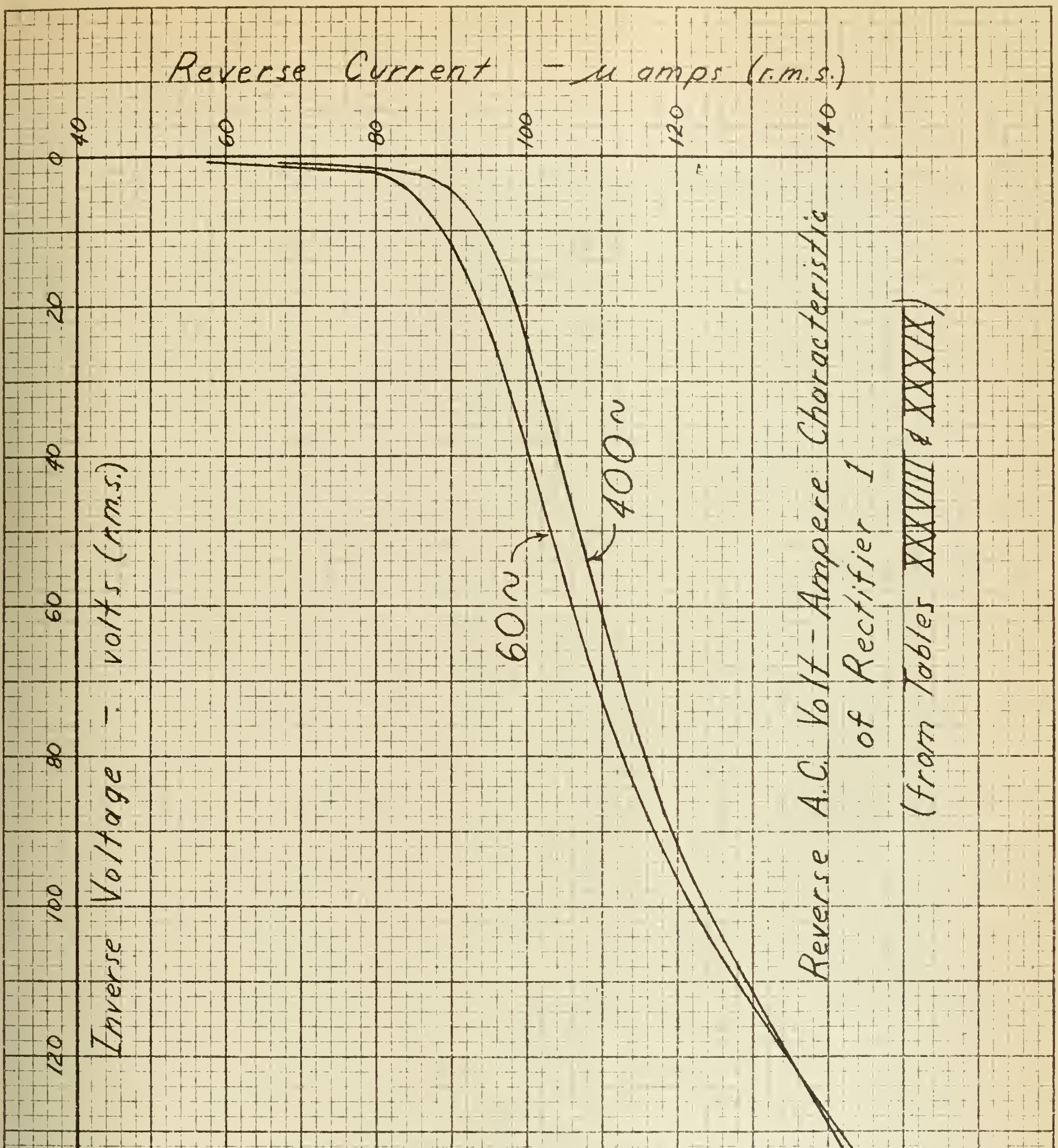
FORWARD A.C. VOLT-AMPERE CHARACTERISTICS
of RECTIFIER 1
(from Tables XXXIV, XXXV & XXXVI)

Fig. 34.



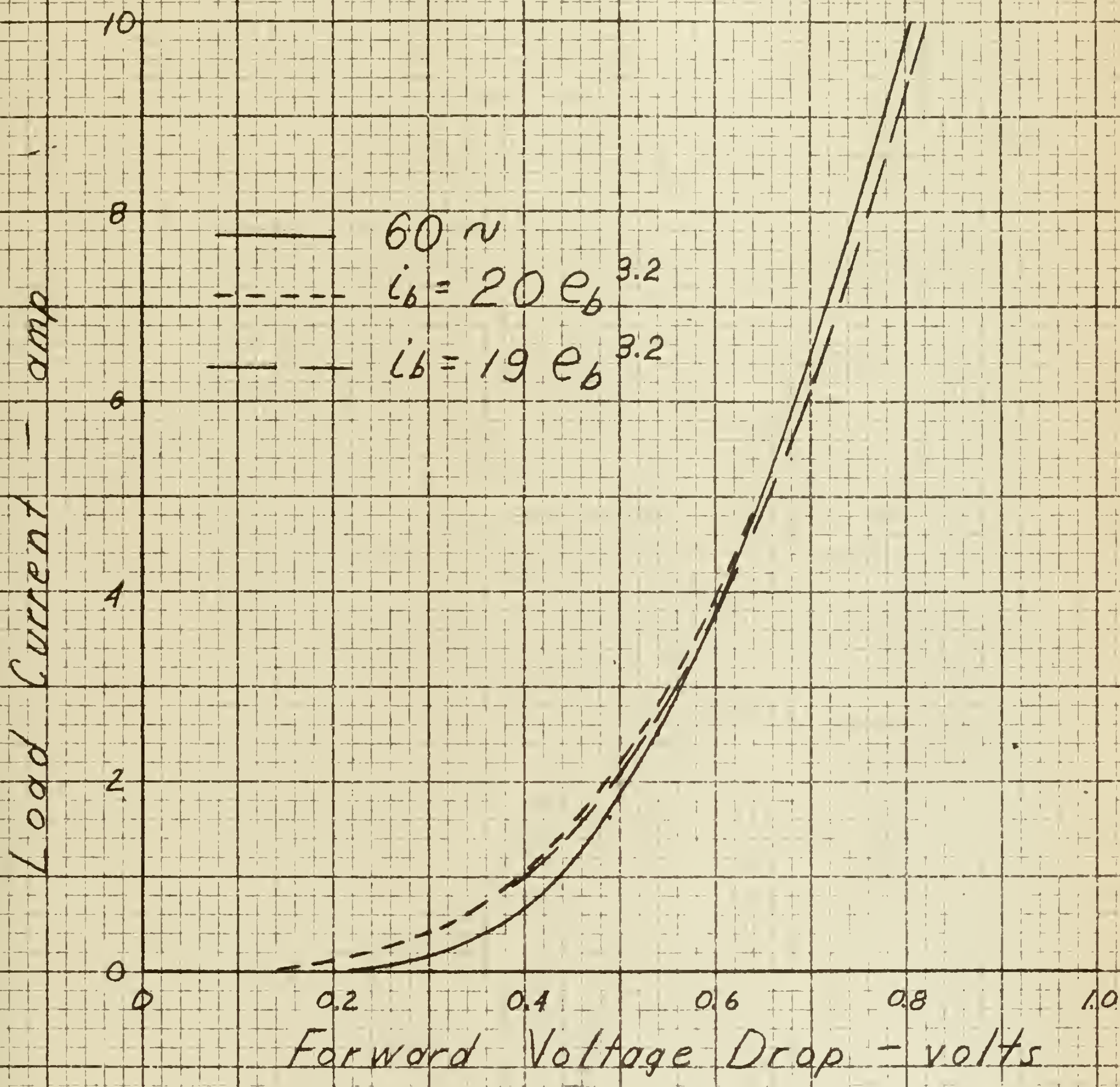
FORWARD A.C. VOLT-AMPERE CHARACTERISTIC
of RECTIFIERS 2 and 3.
(from Table XXXVIII)

Fig. 35.



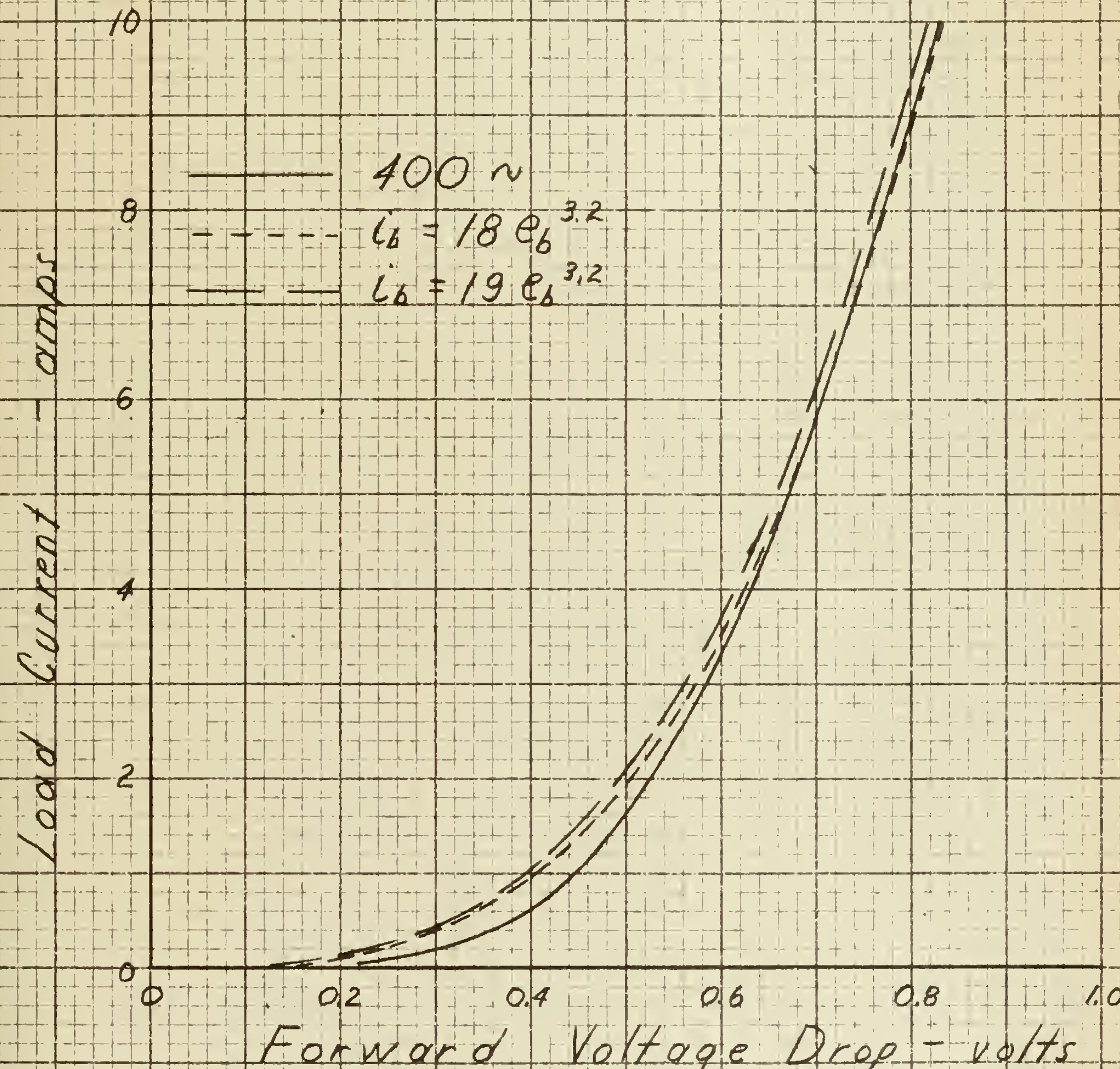
Reverse Current - μ amps (r.m.s.)
40
60
80
100
120
140
0
20
40
60
80
100
120
140
Inverse Voltage - volts (r.m.s.)
60~
400~
Reverse A.C. Volt-Ampere Characteristic
of Rectifier 1
(from Tables XXXVIII & XXXIX)

Fig. 36.



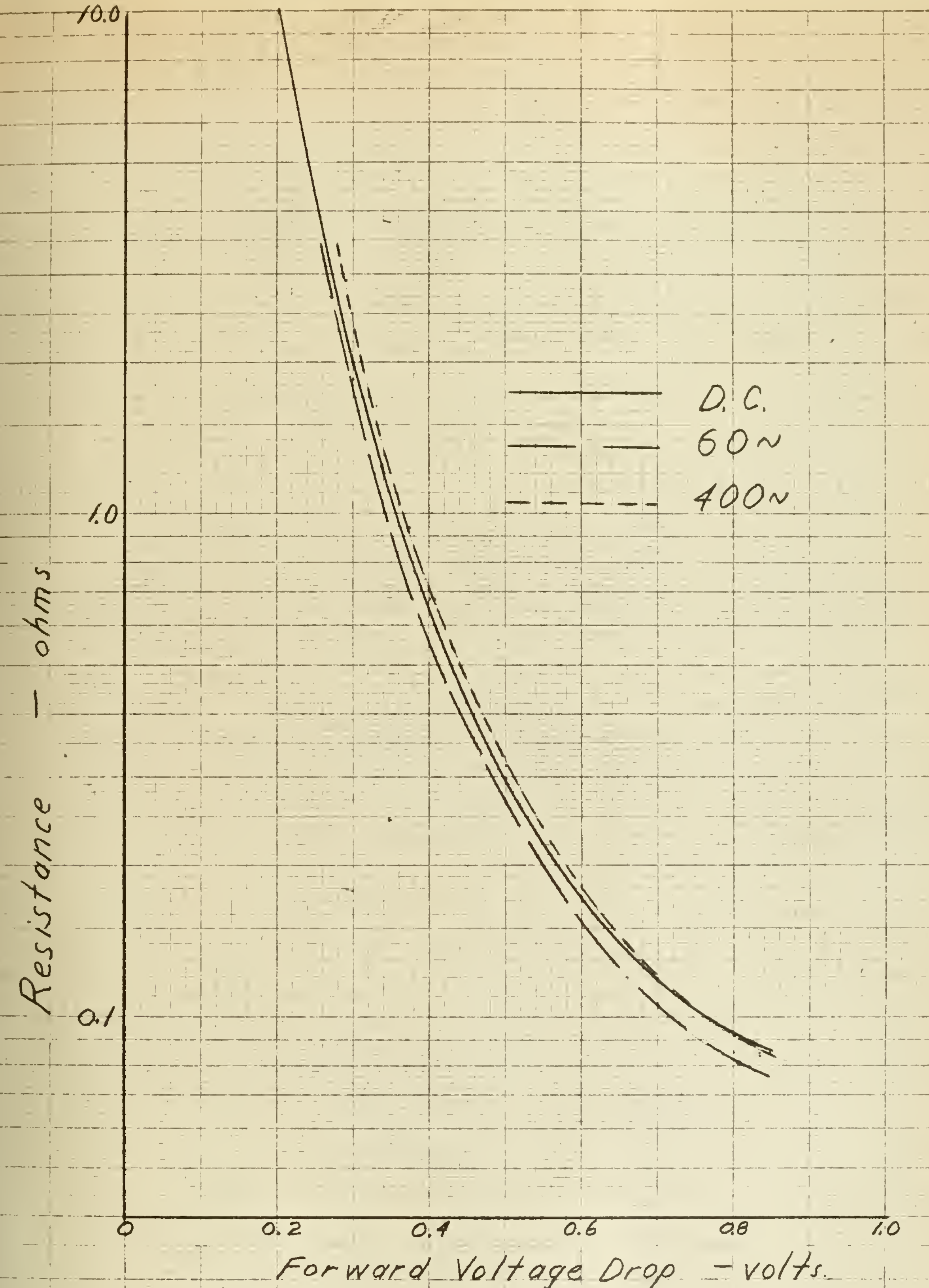
FORWARD 60~ VOLT-AMPERE CHARACTERISTIC of RECTIFIER 1 and ANALYTIC APPROXIMATIONS.

Fig. 37.



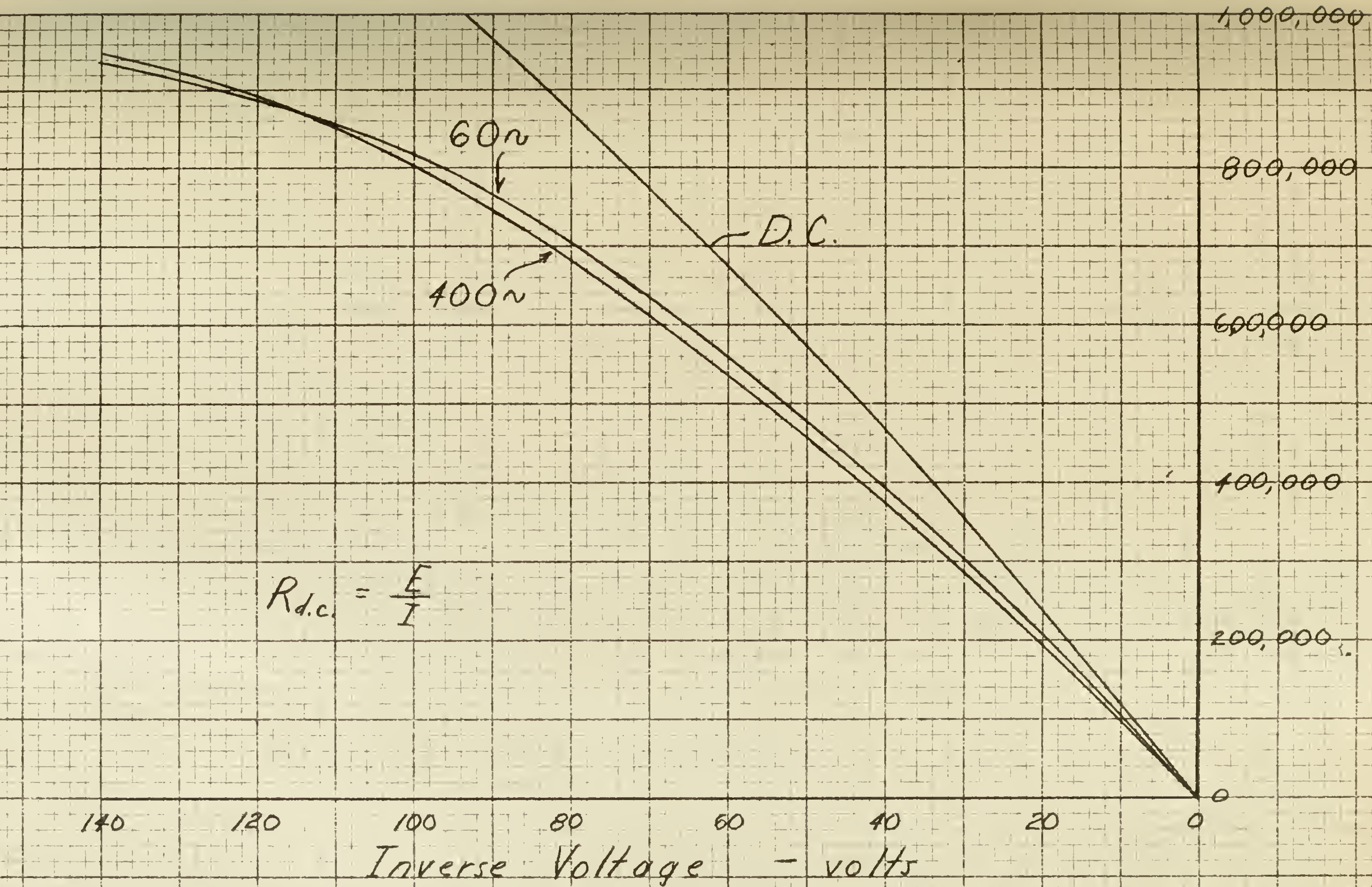
FORWARD 400~ VOLT-AMPERE CHARACTERISTIC of RECTIFIER 1 and ANALYTIC APPROXIMATIONS.

Fig. 38.



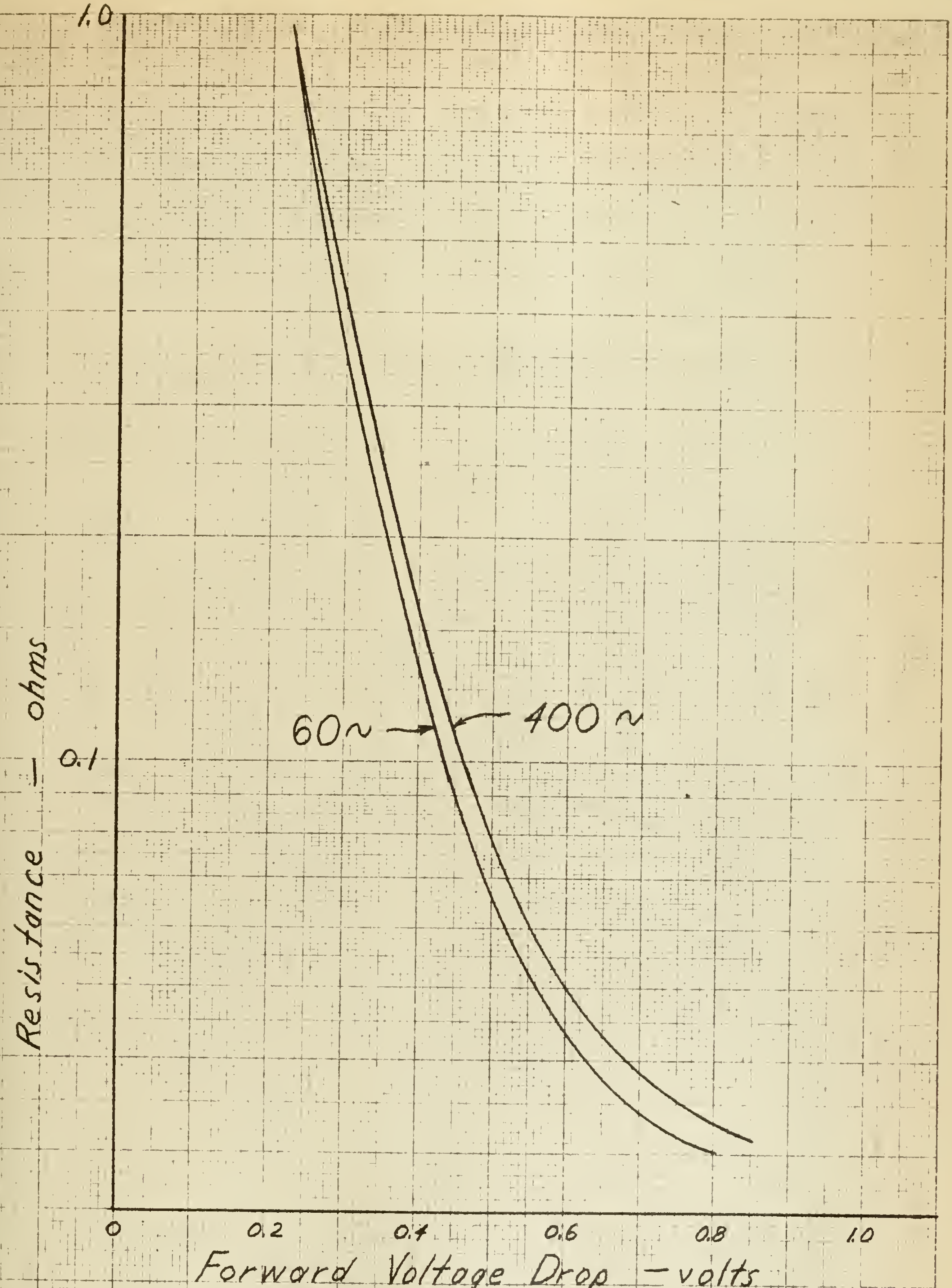
FORWARD D.C. RESISTANCE
(from Tables XL, XLI & XLII)

Fig. 39.



REVERSE D.C. RESISTANCE
(from Tables XL, XLI & XLII)

Fig. 40.



FORWARD A.C. RESISTANCE
(from Tables XLIII & XLIV)

Fig. 41.

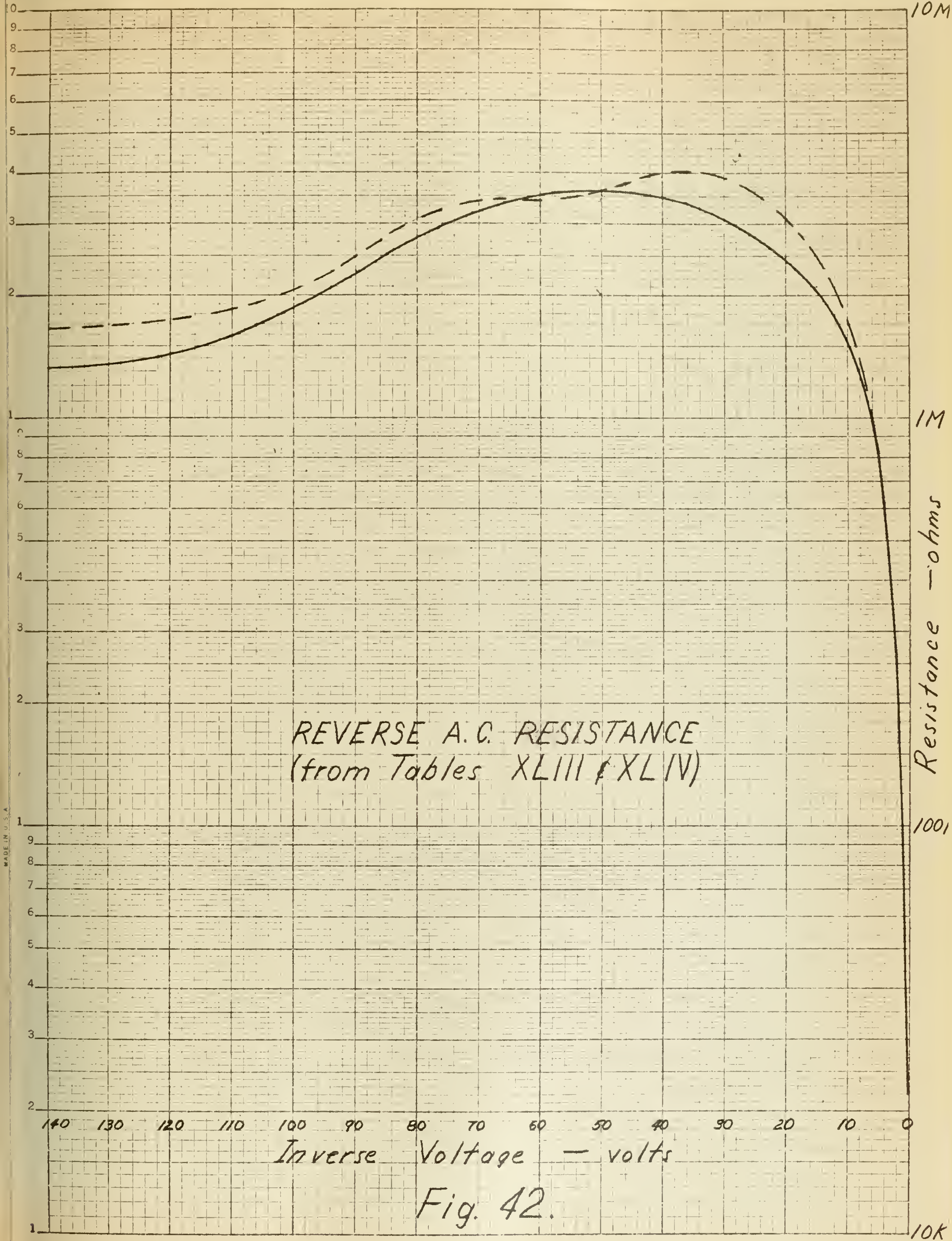

REVERSE A.C. RESISTANCE
(from Tables XLIII & XLIV)
140 130 120 110 100 90 80 70 60 50 40 30 20 10 0
Inverse Voltage — volts
Resistance — ohms
10M
1M
100K
10K
MADE IN U.S.A.

Fig. 42.

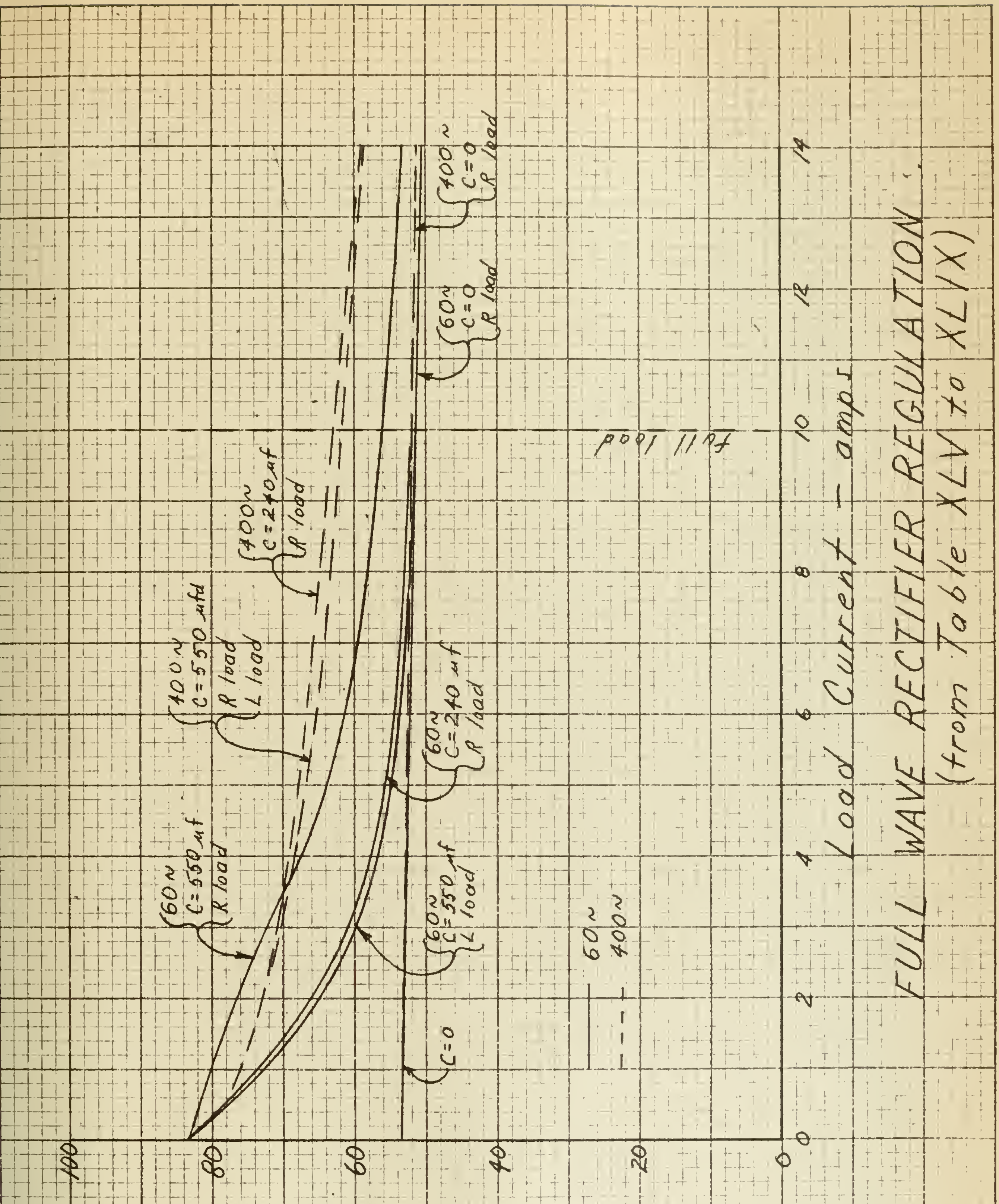
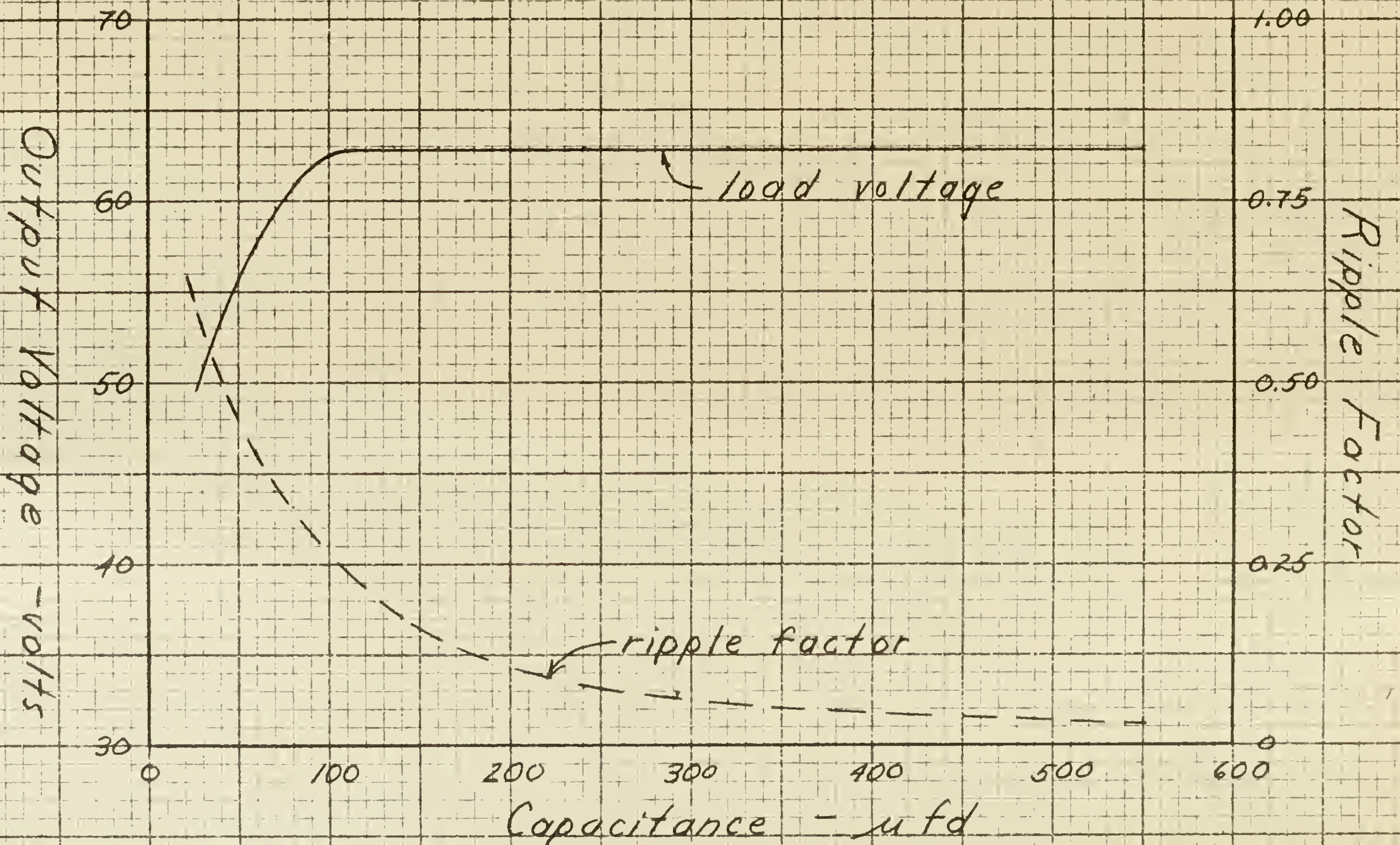

FULL WAVE RECTIFIER REGULATION
(from Table XLV to XLIX)
Load Current — amps
Output Voltage — volts
0
2
4
6
8
10
12
14
0
20
40
60
80
100
full load
60~
400~
C=0
60~ C=550 mf R load
400~ C=550 mfd R load L load
400~ C=240 mf R load
60~ C=550 mf L load
60~ C=240 mf R load
60~ C=0 R load
400~ C=0 R load

Fig. 43.



EFFECT of CAPACITANCE on FULL LOAD OUTPUT VOLTAGE of a FULL WAVE RECTIFIER with 400 CYCLES.
(from Table XLVIII)

Fig. 44.

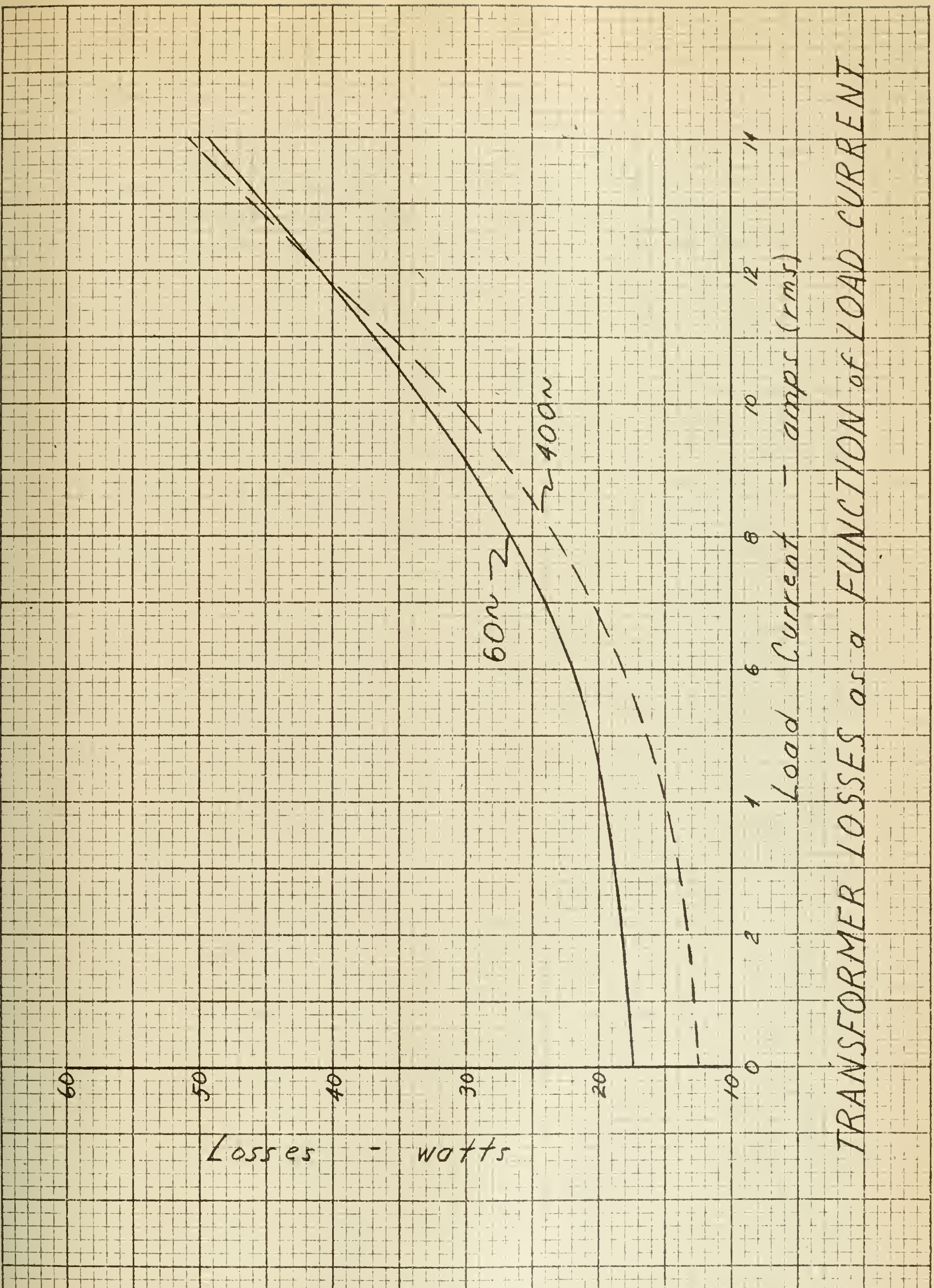
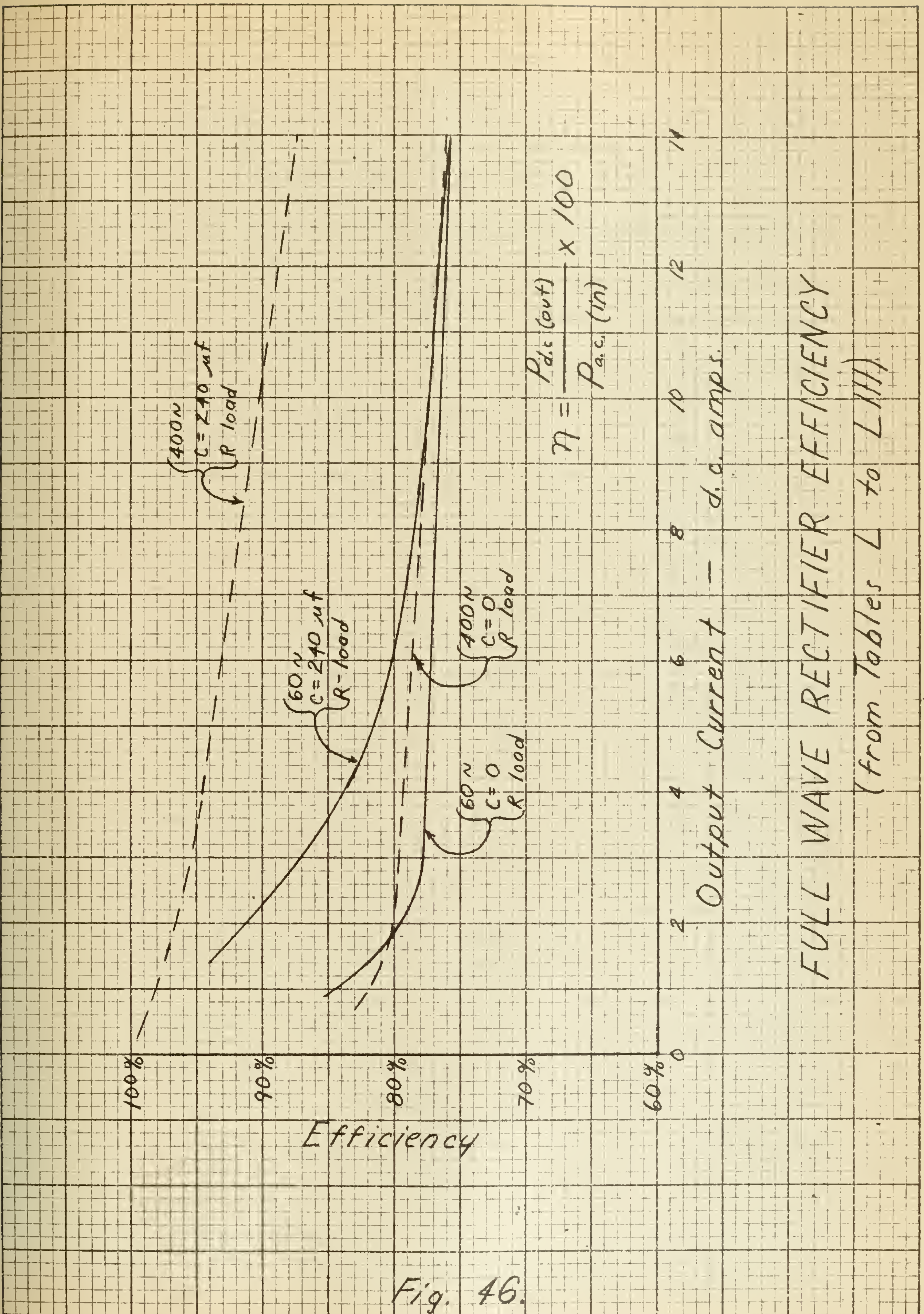

TRANSFORMER LOSSES as a FUNCTION of LOAD CURRENT
Load Current - amps (rms)
Losses - watts
60~
400~
0
2
4
6
8
10
12
14
10
20
30
40
50
60

Fig. 45.



FULL WAVE RECTIFIER EFFICIENCY

(from Tables L to LIII)

Fig. 46.

APPENDIX B

PHOTOGRAPHIC RESULTS

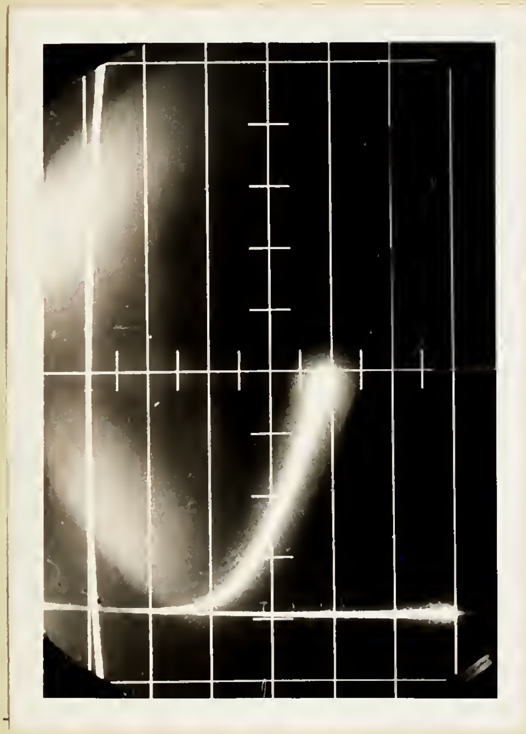
The following pages contain photographs of the voltage and current waveforms observed across the load and the rectifier. The photographs were taken with a Bolsey 35 mm camera. A Tektronix oscilloscope was used.

(a)

Terminal points:

I = 10 amps.

E = 0.908 volts.



(b)

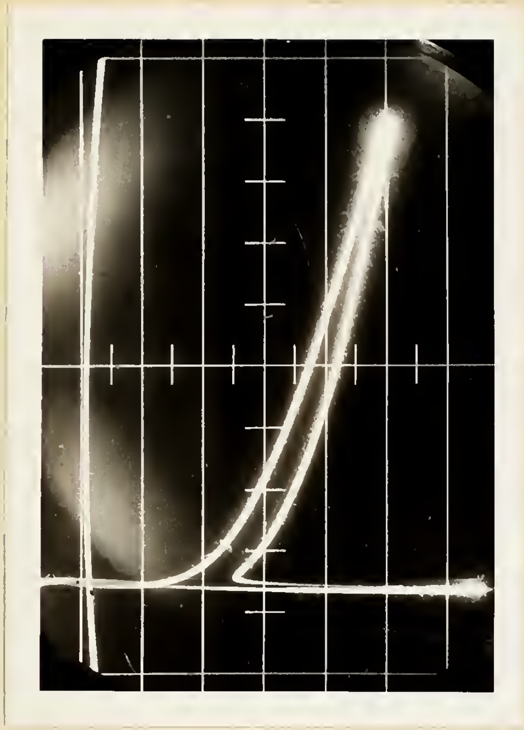
Terminal points:

I = 5 amps.

E = 0.775 volts.

THE FORWARD 60 CYCLE VOLT-AMPERE CHARACTERISTIC OF RECTIFIER 1.

Fig. 47.

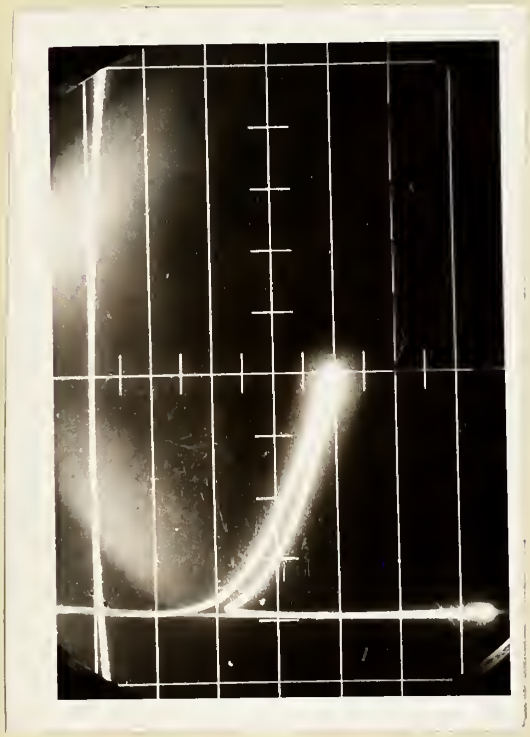


(a)

Terminal points:

I = 10 amps.

E = 0.844 volts.



(b)

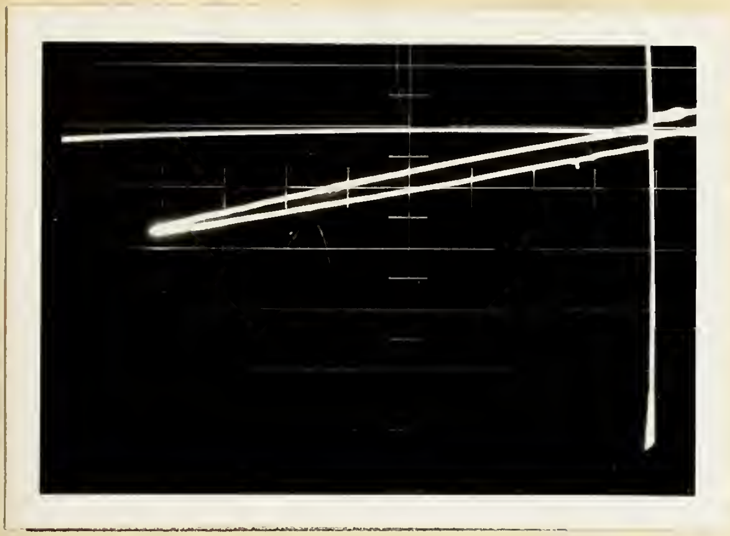
Terminal points:

I = 5 amps.

E = 0.640 volts.

THE FORWARD 400 CYCLE VOLT-AMPERE CHARACTERISTIC OF RECTIFIER 1.

Fig. 48.

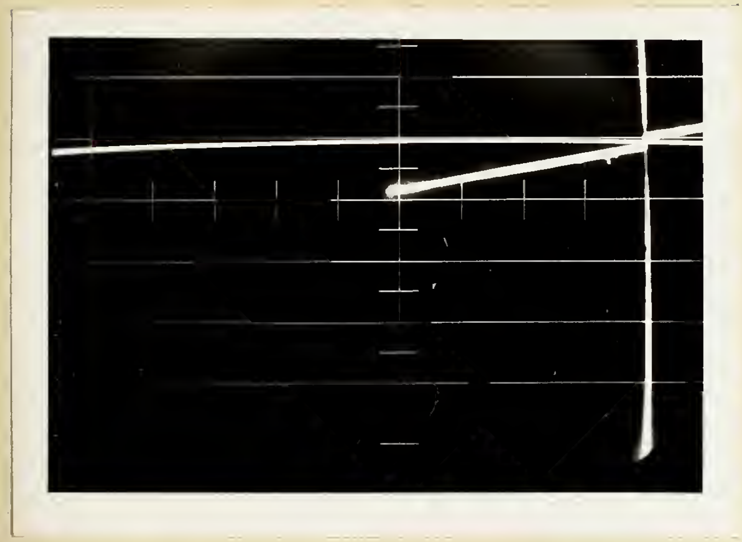


Terminal points:

E = 140 volts

I = 149 u amps

(a)



Terminal points:

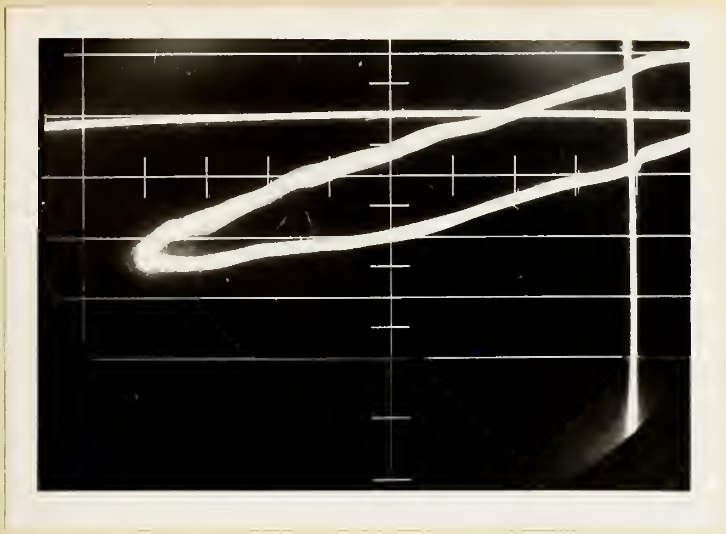
E = 70 volts

I = 110 u amps

(b)

THE REVERSE 60 CYCLE VOLT-AMPERE CHARACTERISTIC OF RECTIFIER 1

Fig. 49.



Terminal points:

E = 140 volts

I = 147 u amps

(a)

Terminal points:

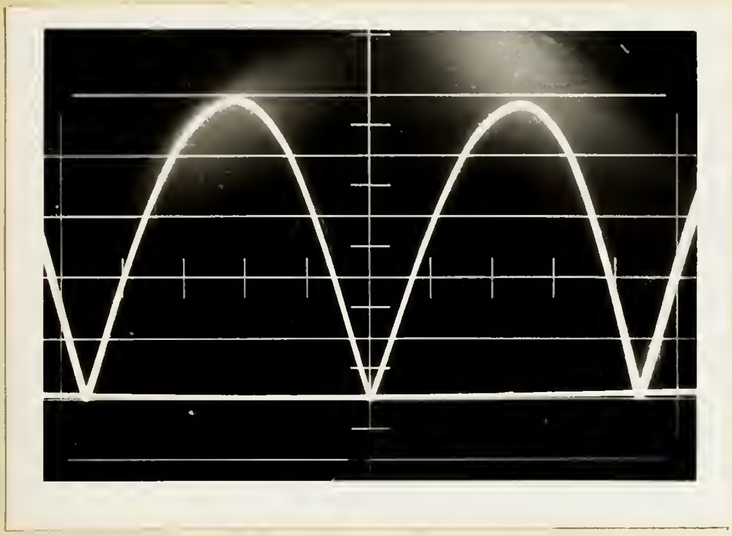
E = 70 volts

I = 112 u amps

(b)

THE REVERSE 400 CYCLE VOLT-AMPERE CHARACTERISTIC OF RECTIFIER 1.

Fig. 50.



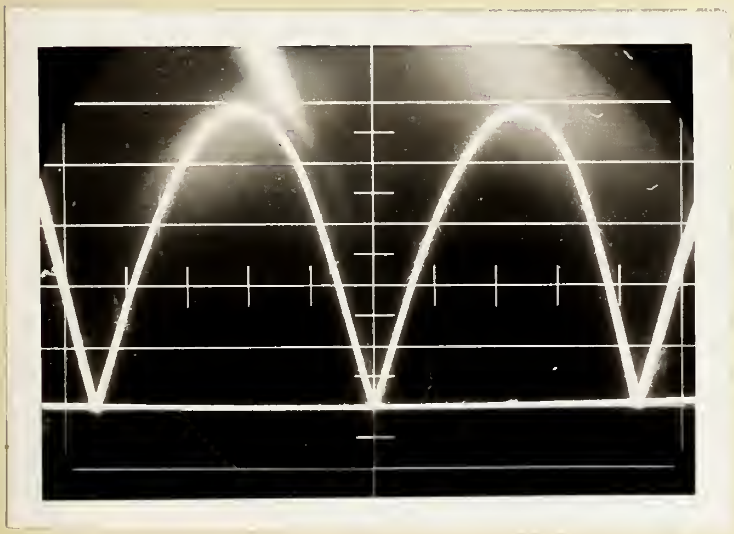
60 cycles.

Resistive load.

No capacitance.

84 volts peak.

(a)



400 cycles.

Resistive load.

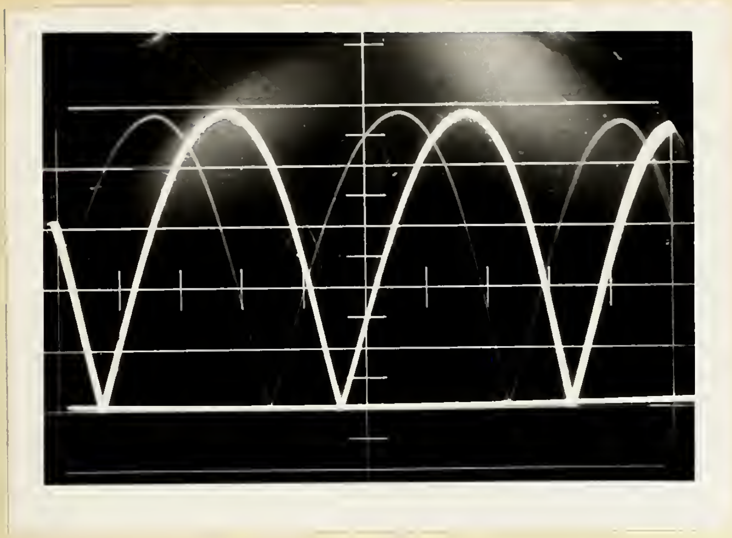
No capacitance.

83 volts peak.

(b)

FULL LOAD OUTPUT VOLTAGE WAVEFORM OF RECTIFIER 1 WITH NO FILTER.

Fig. 51.



60 cycles.

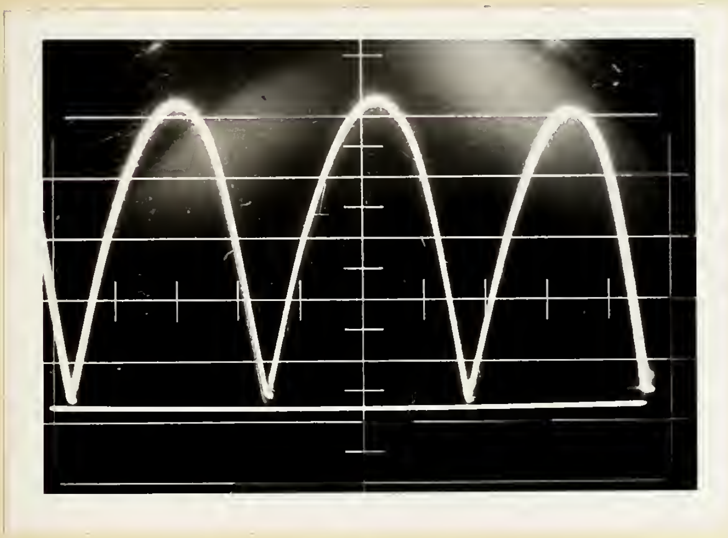
Resistive load.

No capacitance.

10 amp load current.

14.9 amp peak current.

(a)



400 cycles.

Resistive load.

No capacitance.

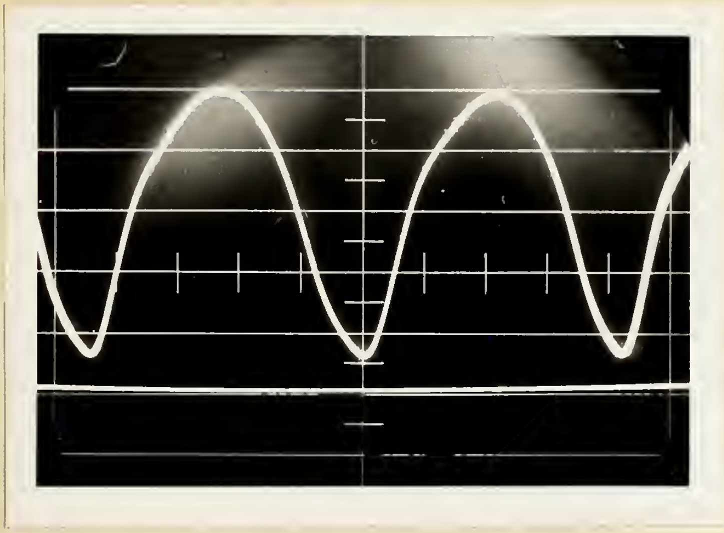
10 amp load current.

15.5 amp peak current.

(b)

FULL LOAD OUTPUT CURRENT WAVEFORM OF RECTIFIER 1 WITH NO FILTER.

Fig. 52.



60 cycles.

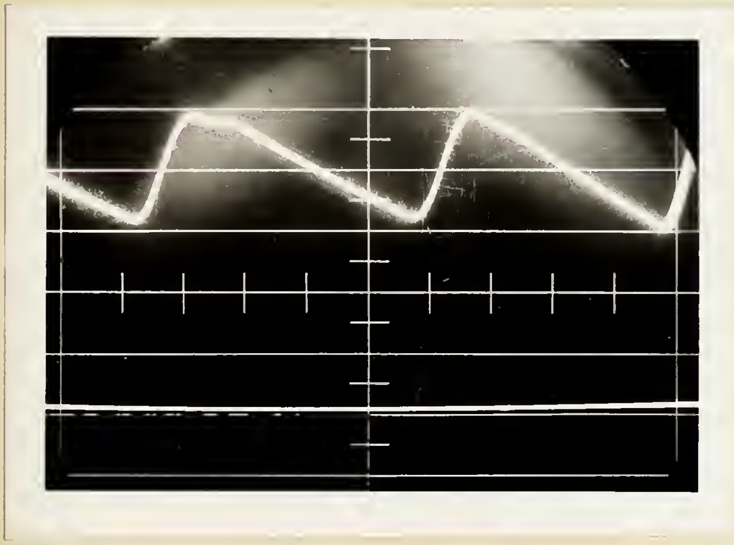
Resistive load.

240 ufd capacitance.

10 amp load current

ripple factor = 0.483

(a)



60 cycles.

Resistive load.

240 ufd capacitance.

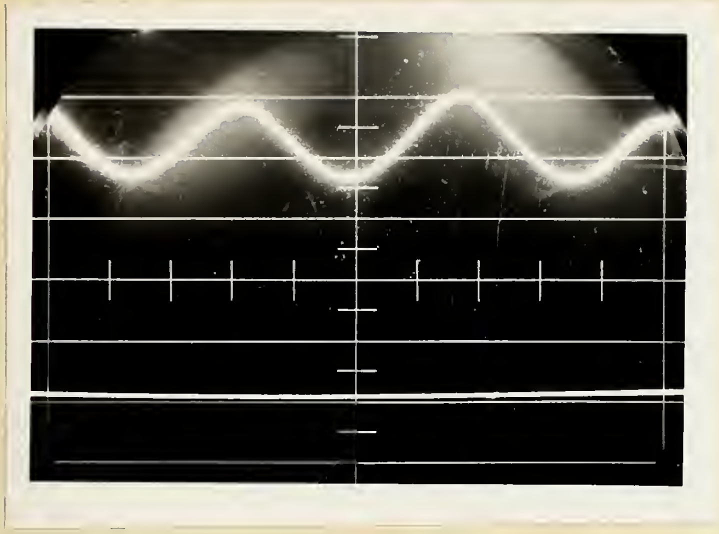
1.2 amp load current.

ripple factor = 0.150

(b)

OUTPUT VOLTAGE WAVEFORMS OF RECTIFIER 1 WITH 240 ufd CAPACITOR FILTOR AND 60 CYCLES.

Fig. 53.



400 cycles.

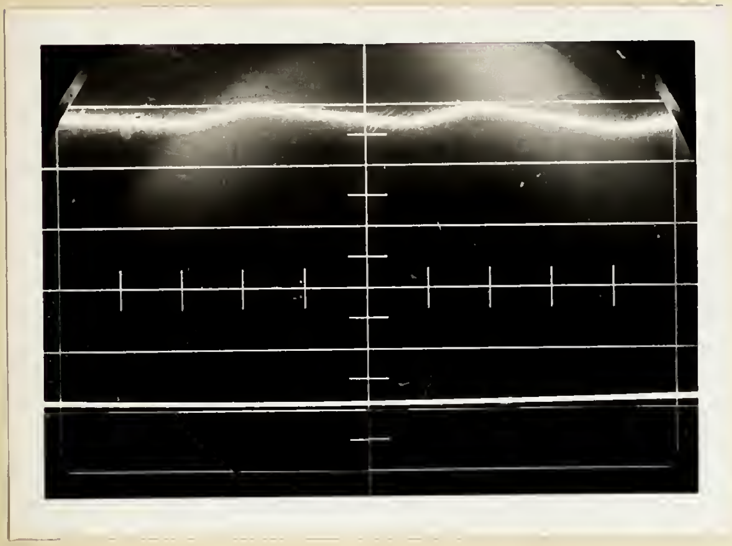
Resistive load.

240 ufd capacitor.

10 amp load current.

ripple factor = 0.098

(a)



400 cycles.

Resistive load.

240 ufd capacitor.

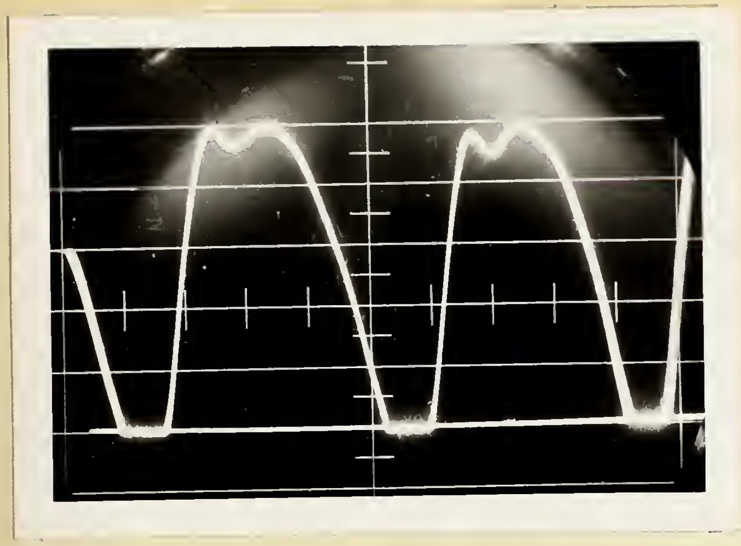
1.28 amp load current.

ripple factor = 0.018

(b)

OUTPUT VOLTAGE WAVEFORMS OF RECTIFIER 1 WITH 240 ufd CAPACITOR FILTER AND 400 CYCLES.

Fig. 54.



60 cycles.

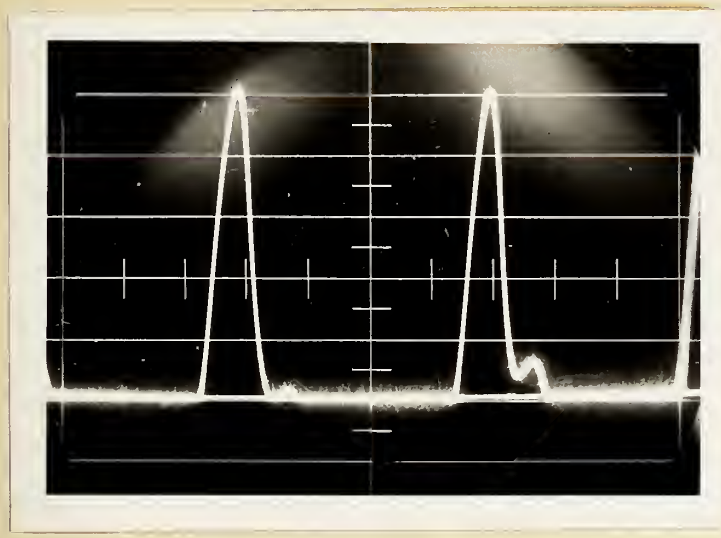
Resistive load.

240 ufd capacitor.

10 amp. load current.

15.07 amp peak current.

(a)



60 cycles.

Resistive load.

240 ufd capacitor.

1.20 amp load current.

7.46 amp peak current.

(b)

WAVEFORMS OF COMBINED CURRENT FROM RECTIFIER 1 WITH 240 ufd CAPACITOR FILTER AND 60 CYCLES.

Fig. 55.

400 cycles.

Resistive load.

240 ufd capacitor.

10 amp load current.

22.9 & 20.5 ampere peak current.

(a)

400 cycles.

Resistive load.

240 ufd capacitor.

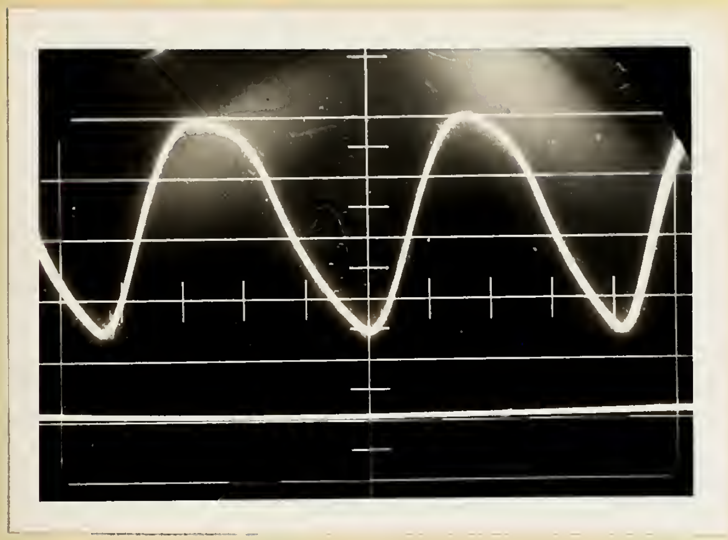
1.27 amp load current.

4.99 & 4.07 amp peak current.

(b)

WAVEFORMS OF COMBINED CURRENT FROM RECTIFIER 1 WITH 240 ufd CAPACITOR FILTER AND 400 CYCLES.

Fig. 56.



60 cycles.

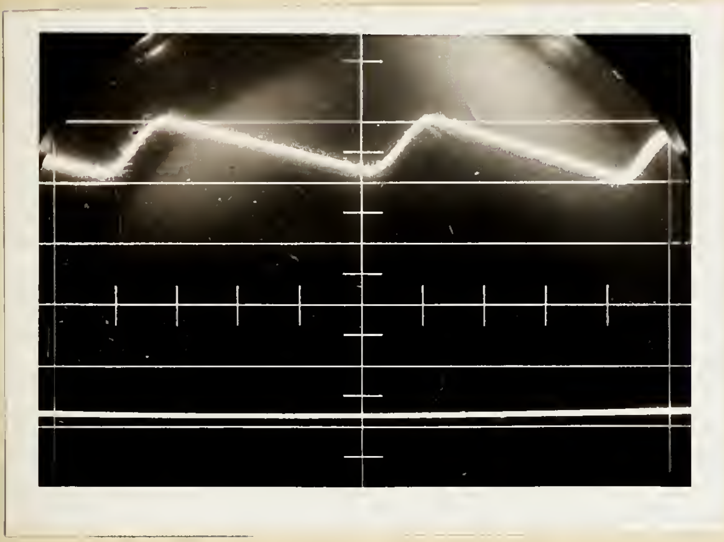
Resistive load.

550 ufd capacitor.

10 amp load current.

ripple factor = 0.392

(a)



60 cycles.

Resistive load.

550 ufd capacitor.

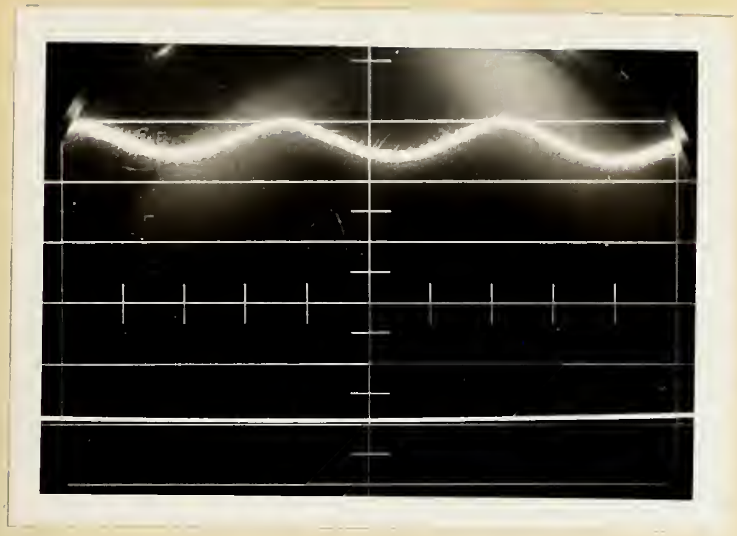
1.33 amp load current.

Ripple factor = 0.051

(b)

OUTPUT VOLTAGE WAVEFORMS OF RECTIFIER 1 WITH 550 ufd CAPACITOR FILTER AND 60 CYCLES.

Fig. 57.



400 cycles.

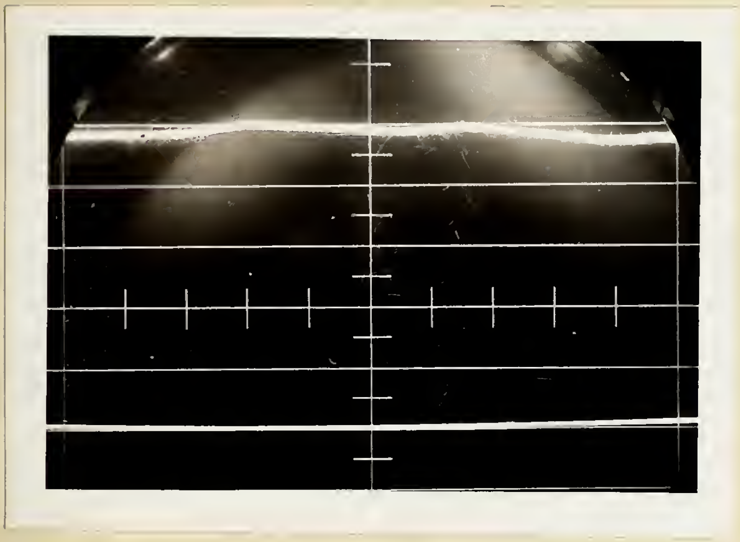
Resistive load.

550 ufd capacitor.

10. amp load current.

Ripple factor = 0.037

(a)



400 cycles.

Resistive load.

550 ufd capacitor.

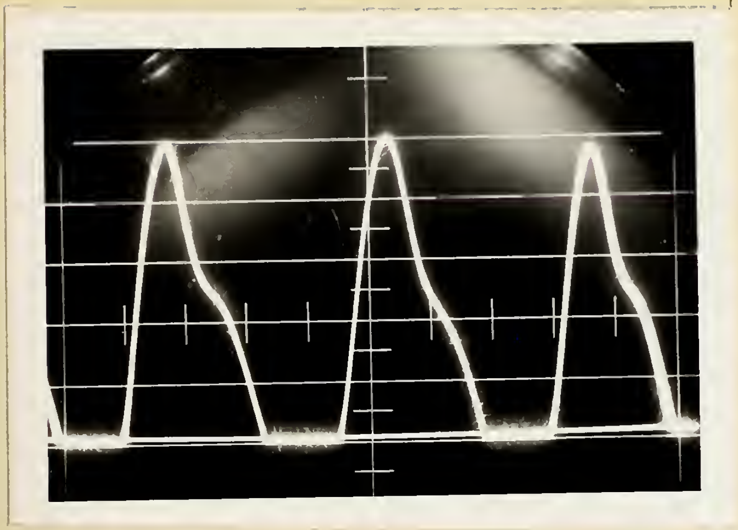
1.27 amp load current.

Ripple factor = 0.006

(b)

OUTPUT VOLTAGE WAVEFORMS OF RECTIFIER 1 WITH 550 ufd CAPACITOR FILTER AND 400 CYCLES.

Fig. 58.



60 cycles.

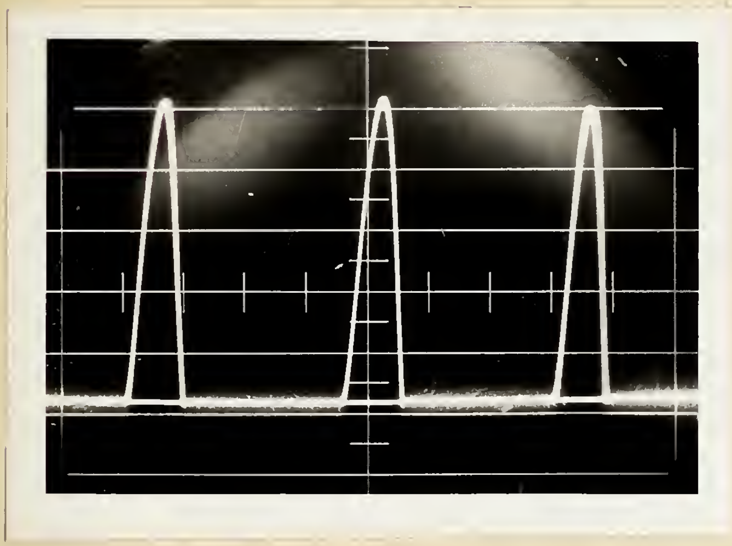
Resistive load.

550 ufd capacitor.

10 amp load current.

26.5 amp peak current.

(a)



60 cycles.

Resistive load.

550 ufd capacitor.

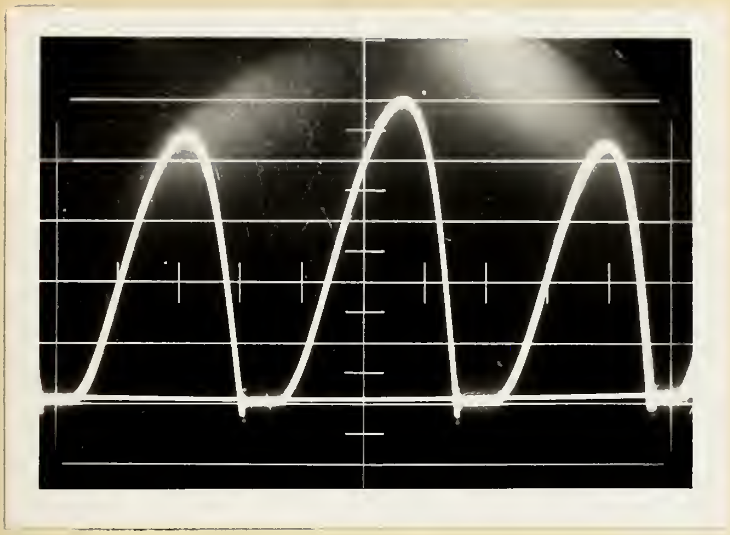
1.20 amp load current.

7.43 amp peak current.

(b)

WAVEFORMS OF COMBINED CURRENT FROM RECTIFIER 1 WITH 550 ufd CAPACITOR FILTER AND 60 CYCLES.

Fig. 59.



400 cycles.

Resistive load.

550 ufd capacitor.

10.18 amp load current.

22.8 & 19.8 amp peak current.

(a)

400 cycles.

Resistive load.

550 ufd capacitor.

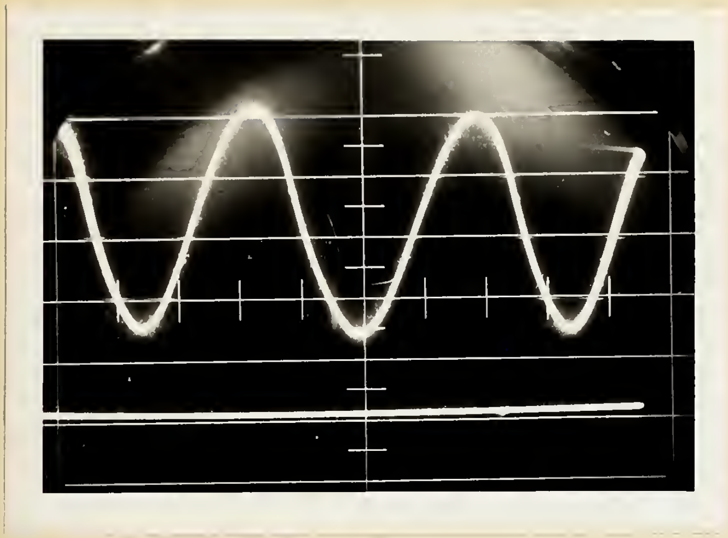
1.20 amp load current.

5.07 & 4.34 amp peak current.

(b)

WAVEFORMS OF COMBINED CURRENT FROM RECTIFIER 1 WITH 550 ufd CAPACITOR FILTER AND 400 CYCLES.

Fig. 60.



400 cycles.

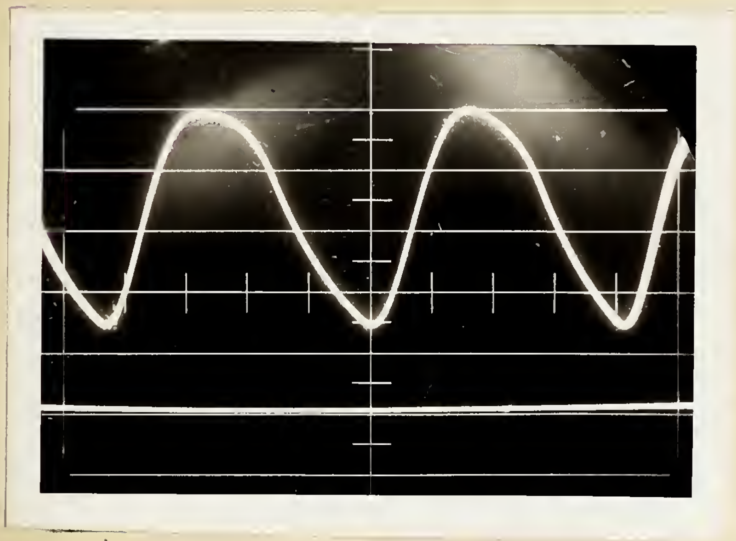
Resistive load.

61 ufd capacitor

10 amp load current.

Ripple factor = 0.392

(a)



60 cycles.

Resistive load.

550 ufd capacitor.

10 amp load current.

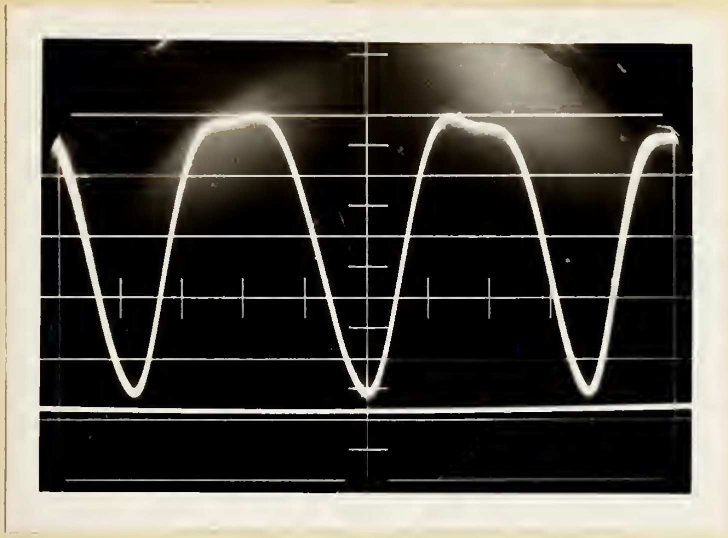
Ripple factor = 0.392

(b)

FILTER CAPACITORS REQUIRED TO GIVE COMPARABLE RIPPLE FACTOR

FOR 60 AND 400 CYCLES.

Fig. 61.



60 cycles.

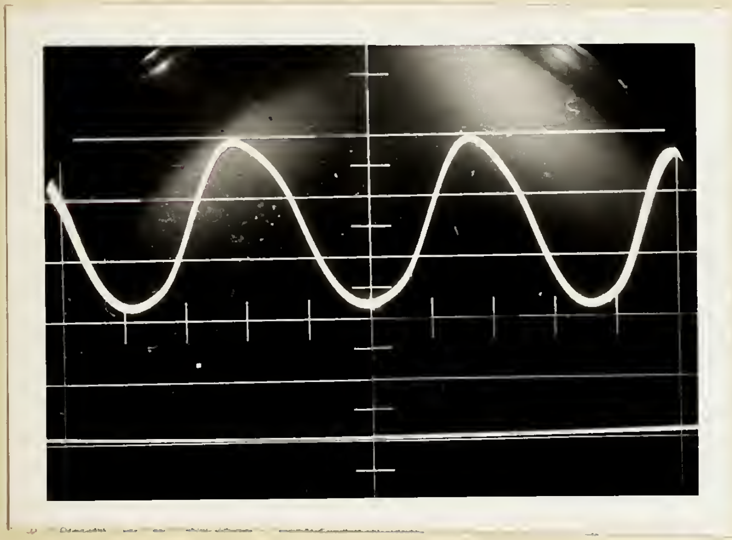
Inductive load.

550 ufd capacitor.

10 amp load current.

Ripple factor = 0.497

(a)



60 cycles.

Inductive load.

550 ufd capacitor.

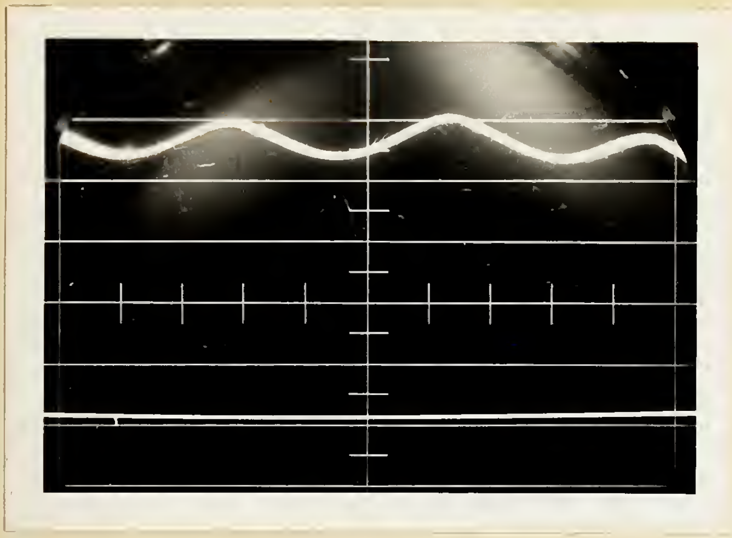
2.83 amp load current.

Ripple factor = 0.227

(b)

OUTPUT VOLTAGE WAVEFORMS OF RECTIFIER 1 WITH 550 ufd CAPACITOR FILTER AND 60 CYCLES.

Fig. 62.



400 cycles.

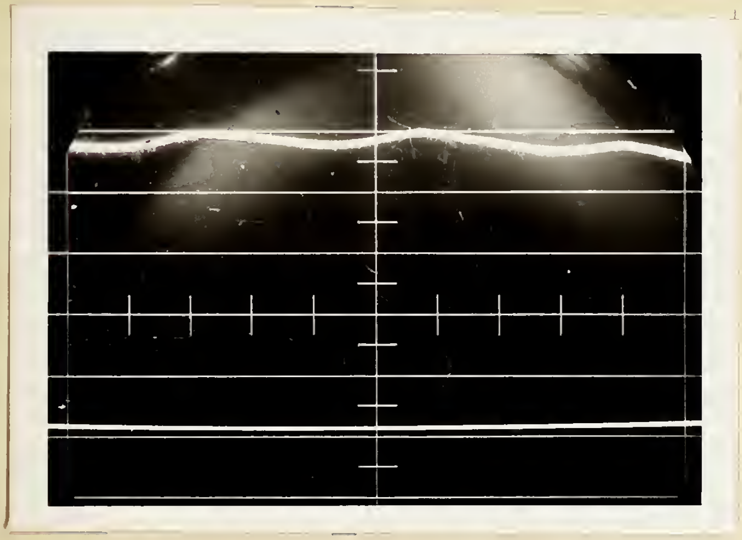
Inductive load.

550 ufd capacitor.

10 amp load current.

Ripple factor = 0.035.

(a)



400 cycles.

Inductive load.

550 ufd capacitor.

2.94 amp load current.

Ripple factor = 0.010.

(b)

OUTPUT VOLTAGE WAVEFORMS OF RECTIFIER 1 WITH 550 ufd CAPACITOR FILTER AND 400 CYCLES.

Fig. 63.

60 cycles.

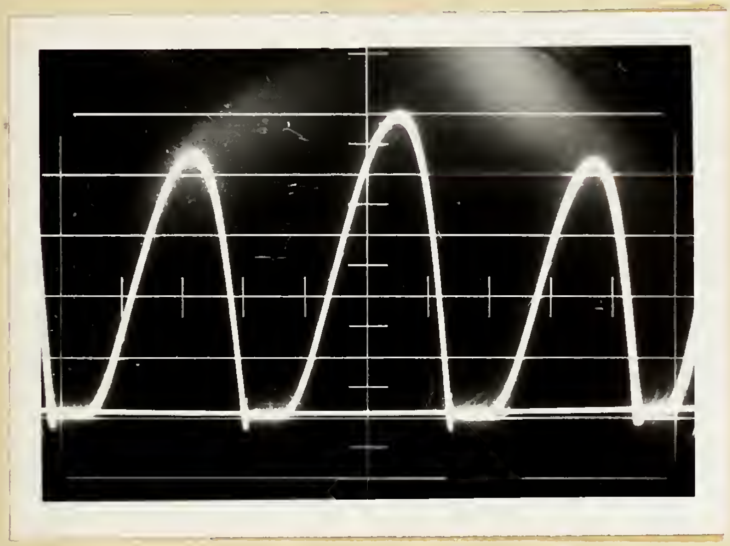
Inductive load.

550 ufd capacitor.

10 amp load current.

20.5 amp peak current.

(a)



400 cycles.

Inductive load.

550 ufd capacitor.

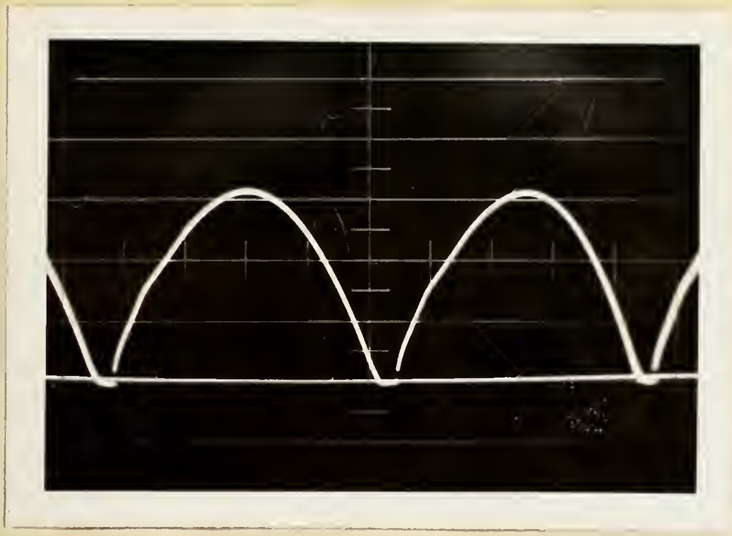
10 amp load current.

22.8 & 20.1 amp peak current.

(b)

WAVEFORMS OF COMBINED CURRENT FROM RECTIFIER 1 WITH 550 ufd CAPACITOR AND INDUCTIVE LOAD.

Fig. 64.



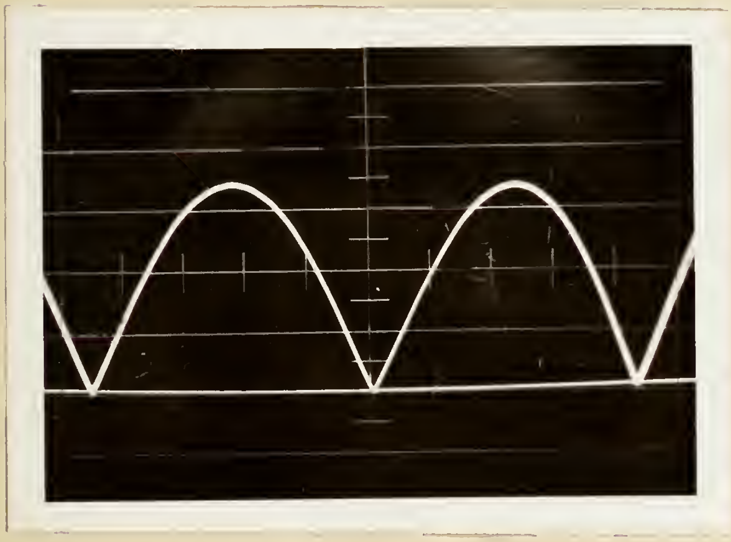
60 cycles.

Resistive load.

No filter.

8 amp load current.

(a)



60 cycles.

Resistive load.

No filter.

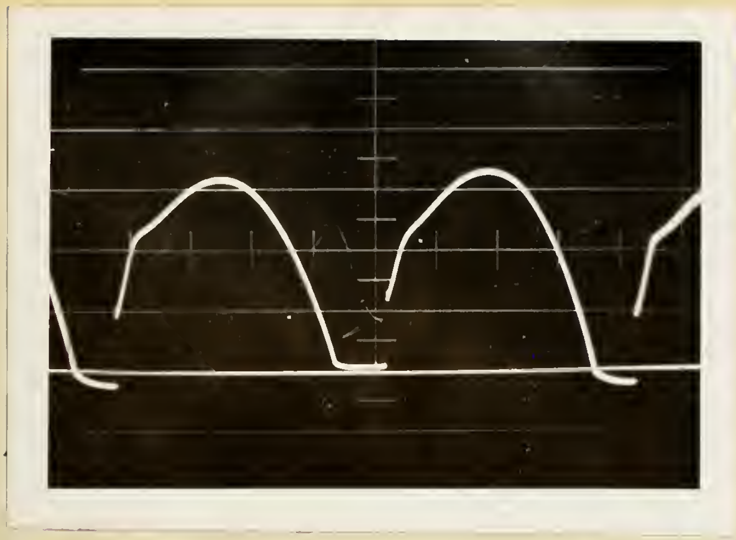
0.4 amp load current.

(b)

OUTPUT VOLTAGE WAVEFORMS OF RECTIFIERS 2 AND 3

FOR 60 CYCLES AND NO FILTER.

Fig. 65.



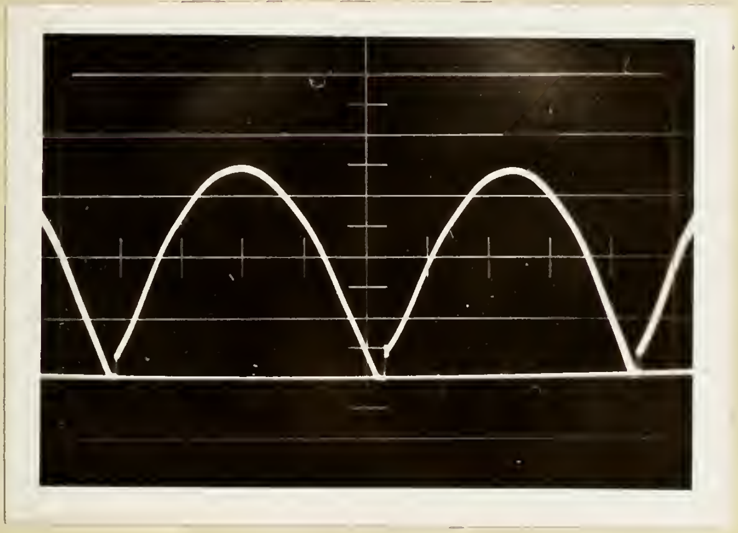
400 cycles.

Resistive load.

No filter.

8 amp load current.

(a)



400 cycles.

Resistive load.

No filter.

0.4 amp load current.

(b)

OUTPUT VOLTAGE WAVEFORMS OF RECTIFIERS 2 AND 3

FOR 400 CYCLES AND NO FILTER.

Fig. 66.

APPENDIX C

TABLES

The following pages contain tables of the actual data taken during the tests.

TABLE I

RECTIFIER D.C. FORWARD VOLTAGE DROP vs TIME

I, amp.	t min.	V, volts	T °C
1.0	0.5	0.45	23.0
1.0	1.0	0.45	23.0
1.0	1.5	0.45	23.1
1.0	2.0	0.45	23.2
1.0	3.0	0.45	23.3
1.0	5.0	0.45	23.3
5.0	0.5	0.66	24.1
5.0	1.0	0.66	24.8
5.0	1.5	0.66	25.1
5.0	2.0	0.66	25.3
5.0	3.0	0.66	25.5
5.0	5.0	0.66	25.7
10.0	0.5	0.84	24.9
10.0	1.0	0.84	26.2
10.0	1.5	0.84	27.2
10.0	2.0	0.84	27.9
10.0	3.0	0.84	28.2
10.0	5.0	0.84	28.7

TABLE II

RECTIFIER 60~ FORWARD VOLTAGE DROP
vs TIME

I, amp.	t min	V. volts	T °C
1.0	0.5	0.440	24.3
1.0	1.0	0.439	24.3
1.0	1.5	0.440	24.4
1.0	2.0	0.440	24.5
1.0	3.0	0.440	24.5
1.0	5.0	0.440	24.6
5.0	0.5	0.654	24.9
5.0	1.0	0.654	25.2
5.0	1.5	0.656	25.5
5.0	2.0	0.654	25.6
5.0	3.0	0.652	25.7
5.0	5.0	0.652	25.8
10.0	0.5	0.814	26.0
10.0	1.0	0.814	26.8
10.0	1.5	0.814	27.1
10.0	2.0	0.813	27.3
10.0	3.0	0.816	27.6
10.0	5.0	0.817	27.9
10.0	8.0	0.816	27.8

TABLE III

RECTIFIER 400~ FORWARD VOLTAGE DROP vs TIME

I, amp.	t min.	V, volts	T °C
1.0	0.5	0.443	25.7
1.0	1.0	0.443	25.7
1.0	1.5	0.443	25.7
1.0	2.0	0.443	25.6
1.0	3.0	0.443	25.6
1.0	5.0	0.443	25.6
5.0	0.5	0.660	26.1
5.0	1.0	0.658	26.4
5.0	1.5	0.658	26.8
5.0	2.0	0.658	26.9
5.0	3.0	0.658	27.0
5.0	5.0	0.658	27.1
10.0	0.5	0.818	27.5
10.0	1.0	0.818	28.1
10.0	1.5	0.819	28.7
10.0	2.0	0.819	29.0
10.0	3.0	0.819	29.0
10.0	5.0	0.818	29.2

TABLE IV

RECTIFIER 2 D.C. FORWARD VOLTAGE DROP vs TIME

I, amp.	t min.	V, volts	T °C
2.0	0.5	0.272	25.1
2.0	1.0	0.272	25.0
2.0	2.0	0.272	24.9
2.0	4.0	0.272	25.0
2.0	6.0	0.272	24.9
2.0	8.0	0.272	24.8
2.0	10.0	0.272	24.8
4.0	0.5	0.312	23.2
4.0	1.0	0.312	23.8
4.0	1.5	0.312	23.9
4.0	2.0	0.312	24.0
4.0	3.0	0.312	24.0
4.0	5.0	0.311	24.0
4.0	10.0	0.311	24.6
8.0	0.5	0.358	25.5
8.0	1.0	0.358	25.9
8.0	2.0	0.357	26.1
8.0	4.0	0.356	26.3
8.0	6.0	0.356	26.4
8.0	8.0	0.355	26.6
8.0	10.0	0.355	26.8

TABLE V

RECTIFIER 3 D.C. FORWARD VOLTAGE DROP vs TIME

I, amp.	t min.	V, volts	T °C
4.0	0.5	0.306	24.9
4.0	1.0	0.305	25.1
4.0	2.0	0.304	25.5
4.0	3.0	0.303	25.7
4.0	5.0	0.303	25.7
4.0	10.0	0.303	26.0
4.0	13.0	0.303	26.0
8.0	0.5	0.341	26.4
8.0	1.0	0.341	27.0
8.0	2.0	0.340	27.3
8.0	3.0	0.340	27.8
8.0	5.0	0.340	27.8
8.0	7.0	0.339	27.9
8.0	10.0	0.339	27.9

TABLE VI

RECTIFIER 1 D.C. REVERSE CURRENT vs TIME

V = 50v

t min	I μ amp
0.25	102.3
0.50	102.2
0.75	102.3
1.00	102.4
1.5	102.5
2.0	102.5
3.0	102.6
4.0	103.0
5.0	103.4
7.0	103.9
10.0	103.9
15.0	103.9
20.0	103.9
25.0	104.0

V = 100v

t min	I μ amp
0.25	110.7
0.50	110.5
0.75	110.5
1.00	110.4
1.5	110.3
2.0	110.2
3.0	110.0
5.0	110.0
8.0	109.9
10.0	109.8
15.0	109.8
20.0	110.2
25.0	110.2
30.0	110.4

TABLE VII

RECTIFIER 1 60~ REVERSE CURRENT vs TIME

$V = 50\,v$

t min.	V_R volts	I μ amp.	T °C
0.25	0.688	118.3	23.1
0.50	0.688	118.3	23.1
1.00	0.687	118.2	23.1
1.5	0.688	118.3	23.1
2.0	0.687	118.2	23.1
3.0	0.691	118.8	23.1
5.0	0.695	119.6	23.2
7.0	0.697	119.9	23.2
10.0	0.698	120.1	23.2
15.0	0.698	120.1	23.2
20.1	0.698	120.1	23.2

$V = 100\,v$

0.25	0.819	140.8	23.2
0.50	0.819	140.8	23.2
1.00	0.820	141.1	23.2
1.5	0.820	141.1	23.2
2.0	0.822	141.5	23.2
3.0	0.823	141.7	23.3
5.0	0.819	140.8	23.3
7.0	0.826	142.2	23.3
10.0	0.822	141.5	23.2
15.0	0.820	141.1	23.1

TABLE VII cont.

RECTIFIER 1 60~ REVERSE CURRENT vs TIME

$V = 130\,v$

t min.	V_R volts	I μ amp.	T °C
0.25	0.944	162.3	23.3
0.50	0.950	163.4	23.4
1.00	0.948	163.2	23.4-
1.5	0.946	162.9	23.4
2.0	0.953	163.9	23.5
3.0	0.946	162.9	23.4
4.0	0.948	163.2	23.5
5.0	0.955	164.3	23.5
7.0	0.961	165.4	23.6
10.0	0.964	165.9	23.7
15.0	0.825	142.0	20.8

opened window

TABLE VIII

RECTIFIER 1 400~ REVERSE CURRENT vs TIME

V=50v

t min.	V_R volts	I μ amp.	T °C
0.25	0.677	116.6	23.1
0.50	0.680	117.0	23.1
1.00	0.688	118.3	23.2
1.5	0.688	118.3	23.2
2.0	0.692	119.1	23.2
3.0	0.700	120.4	23.3
5.0	0.713	122.7	23.3
7.0	0.723	124.3	23.4
10.0	0.739	127.1	23.7
15.0	0.739	127.1	23.7

V=100v

0.25	0.835	143.7	23.2
0.50	0.838	144.1	23.2
1.00	0.832	143.2	23.2
1.5	0.832	143.2	23.15
2.0	0.825	142.0	23.1
3.0	0.828	142.4	23.0
5.0	0.857	147.6	23.7
7.0	0.802	138.0	22.6
10.0	0.807	138.9	22.9
15.0	0.834	143.5	23.2

TABLE VIIII continued

V = 130v

t min	V_R volts	I μ amp.	T °C
0.25	0.958	164.8	23.2
0.50	0.962	165.6	23.3
1.00	0.970	166.9	23.5
1.5	0.974	167.6	23.45
2.0	0.975	167.7	23.5
3.0	0.988	170.0	23.7
5.0	0.990	170.3	23.7
7.0	0.988	170.0	23.7
10.0	0.907	156.1	22.3
15.0	0.955	164.4	23.25

TABLE IX

RECTIFIER 3 D.C. REVERSE CURRENT vs TIME

$V = 50v$

t min.	I_t ma	$I_{22°}$ ma	T °C
0.5	39.7	38.9	23.4
1.0	43.3	41.8	24.3
1.5	45.3	43.5	24.9
2.0	46.3	44.0	24.9
2.5	47.0	44.7	25.0
3.0	47.3	44.8	25.1
3.5	47.4	44.9	25.1
4.0	47.4	44.8	25.2
4.5	47.4	44.8	25.3
5.0	47.4	44.8	25.3
6.0	47.4	44.8	25.3
7.0	47.1	44.5	25.3
8.0	46.9	44.3	25.4
10.0	46.2	43.6	25.3
12.0	46.0	43.4	25.4
15.0	45.3	42.7	25.4
18.0	44.7	42.2	25.4
23.0	44.2	41.5	25.6
26.0	43.9	41.3	25.6
30.0	43.6	41.0	25.6
35.0	43.0	40.4	25.7
40.0	42.8	40.2	25.7
45.0	42.4	39.8	25.7
50.0	42.1	39.7	25.3
55.0	42.1	39.6	25.6
60.0	41.7	39.4	25.3
72.0	41.4	39.1	25.3

TABLE X

RECTIFIER 3 D.C. REVERSE CURRENT vs TIME

V= 30v

t min	I_t ma.	$I_{22°}$ ma.	T °C
0.5	24.0	23.2	24.1
1.0	25.3	24.3	24.3
1.5	26.0	25.2	24.6
2.0	26.8	25.6	24.6
2.5	27.0	25.9	24.5
3.0	27.1	26.0	24.5
3.5	27.2	26.1	24.4
4.0	27.2	26.1	24.4
4.5	27.2	26.1	24.4
5.0	27.2	26.1	24.4
6.0	27.1	26.0	24.3
8.0	27.0	25.9	24.3
10.0	26.9-	25.8	24.3
12.0	26.8	25.7	24.3
16.0	26.5	25.4	24.3
23.0	26.1	25.2	24.2
25.0	26.1	25.2	24.2
30.0	26.1	25.1	24.3
35.0	25.9	24.9	24.4
40.0	25.8	24.8	24.3
45.0	25.6	24.6	24.3
50.0	25.4	24.4	24.4
55.0	25.3	24.3	24.3
60.0	25.2	24.2	24.4

TABLE XI

RECTIFIER 3 D.C. REVERSE CURRENT vs TIME

t min	V volts	I_t ma	$I_{22°}$ ma	T °C
0.5	40	30.2	29.6	23.4
1.0		31.0	30.1	23.7
1.5		31.1	30.2	23.8
2.0		31.1	30.2	23.8
3.0		31.1	30.2	23.9
5.0		31.0	30.1	23.9
7.0		30.9	29.9	23.9
10.0		30.9	29.9	23.9
15.0		30.8	29.8	23.9
20.0		30.7	29.8	23.9
25.0		30.6	29.7	23.9
30.0		30.5	29.6	23.9
35.0		30.3	29.4	23.9
37.0-	40	30.6	29.5	24.1
37.0+	0	0.0	0.0	24.1
38.0-	0	0.0	0.0	23.9
38.25	40	29.8	28.9	23.8
38.5		30.0	29.1	23.8
39.0		30.1	29.2	23.9
39.5		30.3	29.4	23.9
40.0		30.3	29.4	23.9
41.0		30.4	29.7	23.9
43.0		30.6	29.6	24.0
45.0		30.7	29.7	24.0
50.0-	40	30.7	29.7	24.0
50.0+	0	0.0	0.0	24.0
53.0-	0	0.0	0.0	23.7
53.25	30	22.9	22.4	23.5
53.5		23.1	22.5	23.5
54.0		23.1	22.5	23.5

TABLE XI continued

t min	V volts	I_t ma	$I_{22°}$ ma	T °C
55.0	30	23.2	22.6	23.6
57.0		23.2	22.6	23.6
60.0		23.2	22.6	23.6
61.0-	30	23.2	22.6	23.6
61.0+	0	0.0	0.0	23.6
63.0-	0	0.0	0.0	23.7
63.25	50	36.9	35.8	23.8
63.5		37.3	36.2	23.9
64.0		37.8	36.5	24.1
65.0		38.2	36.7	24.3
66.0		38.3	36.7	24.6
69.0		38.5	36.7	24.8
72.0		38.6	36.7	24.9
79.0		38.4	36.6	24.8
99.0-	50	38.6	36.7	24.9
99.0+	0	0.0	0.0	24.9
101.0-	0	0.0	0.0	24.8
101.25	60	44.9	43.1	24.4
101.5		45.6	43.5	24.7
102.0		46.1	43.7	25.1
103.0		46.9	44.3	25.4
104.0		46.9	44.3	25.4
105.0		46.7	44.0	25.4
109.0		46.6	43.9	25.4

TABLE XII

RECTIFIER 2 D.C. REVERSE CURRENT vs TIME

t min.	V volts	I_t ma	$I_{22°}$ ma	T °C
0.5	50	8.6	8.49	23.0
1.0		11.3	11.17	23.0
1.5		12.7	12.56	22.9
2.0		13.33	13.19	22.9
2.5		13.76	13.63	22.8
3.0		13.90	13.79	22.9
3.5		13.97	13.83	22.8
4.0		13.98	13.84	22.8
5.0		13.88	13.75	22.8
6.0		13.69	13.57	22.8
7.0		13.48	13.36	22.8
8.0		13.25	13.13	22.8
9.0		13.03	12.92	22.8
10.0		12.82	12.70	22.8
12.0		12.43	12.30	22.8
16.0		11.80	11.66	22.9
20.0		11.28	11.13	22.9
26.0		10.68	10.52	22.9
29.0		10.42	10.26	22.9
35.0		10.08	9.92	23.0
40.0		9.82	9.62	23.0
45.0		9.59	9.38	23.1
50.0		9.39	9.15	23.1
56.0		9.23	8.98	24.0
60.0		9.16	8.90	24.1
65.0		9.02	8.75	24.1
70.0		8.89	8.65	24.0
75.0		8.81	8.57	24.0
80.0		8.72	8.48	24.0
85.0		8.62	8.38	24.0

TABLE XII continued

t min.	V volts	I_T ma	$I_{22°}$ ma	T °C
90.0	50	8.52	8.28	24.0
94.0−	50	8.46	8.23	24.0
94.0+	0	0.0	0.0	24.0
95.0−	0	0.0	0.0	23.9
95.25	50	4.42	4.31	23.8
95.50		5.28	5.15	23.8
95.75		5.99	5.85	23.8
96.0		6.53	6.37	23.8
96.5		7.23	7.07	23.8
97.0		7.63	7.44	23.9
98.0		8.00	7.79	23.9
99.0		8.14	7.93	23.9
100.0		8.21	8.00	23.9
102.0		8.27	8.05	23.9
104.0		8.24	8.02	24.0
108.0		8.20	7.98	24.0
115.0		8.16	7.94	24.0
116.0−	50	8.14	7.92	24.0
116.0+	0	0.0	0.0	24.0
121.0−	0	0.0	0.0	23.8
121.25	50	4.75	4.64	23.8
121.50		5.47	5.34	23.8
121.75		6.01	5.86	23.8
122.0		6.42	6.27	23.7
122.5		7.03	6.86	23.8
123.0		7.38	7.20	23.8
124.0		7.77	7.58	23.8
125.0		7.96	7.75	23.9
126.0		8.03	7.82	23.9
127.0		8.08	7.87	23.9

TABLE XII continued

t min.	V volts	I_T ma	$I_{22°}$ ma	T °C
128.0	50	8.08	7.87	23.9
134.0-	50	8.00	7.79	23.9
134.0+	0	0.0	0.0	23.9
144.0-	0	0.0	0.0	23.7
144.25	50	4.96	4.85	23.7
144.50		5.73	5.60	23.7
144.75		6.24	6.10	23.7
145.0		6.60	6.44	23.8
145.5		7.09	6.92	23.8
146.0		7.41	7.23	23.8
147.0		7.78	7.59	23.8
148.0		7.94	7.73	23.9
149.0		8.02	7.81	23.9
150.0		8.07	7.86	23.9
151.0		8.07	7.86	23.9
153.0	50	8.04	7.82	24.0
153.25	70	9.94	9.67	24.0
153.50		10.07	9.78	24.1
153.75		10.12	9.83	24.1
154.0		10.19	9.88	24.2
154.5		10.24	9.95	24.2
155.0		10.27	9.96	24.2
156.0		10.30	9.96	24.3
158.0		10.28	9.95	24.3
160.0		10.21	9.89	24.3

TABLE XIII
RECTIFIER 2 D.C. REVERSE CURRENT vs TIME

$V = 70$ volts

t min.	I_T ma	$I_{22°}$ ma	T °C
0.5	7.2	7.2	22.0
1.0	9.5	9.49	22.1
1.5	10.7	10.67	22.3
2.0	11.31	11.21	22.7
2.5	11.74	11.62	22.9
3.0	12.00	11.87	22.9
4.0	12.29	12.03	23.0
5.0	12.37	12.23	23.1
6.0	12.31	12.20	23.1
7.0	12.26	12.14	23.2
8.0	12.15	12.08	23.2
9.0	12.03	11.97	23.2
10.0	11.91	11.87	23.2
11.0	11.77	11.73	23.2
13.0	11.51	11.34	23.2
15.0	11.24	11.08	23.2
17.0	11.02	10.88	23.1
20.0	10.71	10.57	23.1
24.0	10.47	10.32	23.1
28.0	10.26	10.10	23.2
32.0	10.06	9.91	23.2
36.0	9.88	9.72	23.3
40.0	9.70	9.55	23.3
45.0	9.54	9.38	23.3
50.0	9.42	9.27	23.3
55.0	9.29	9.14	23.3
60.0	9.19	9.02	23.4

TABLE XIV

RECTIFIER 1 D.C. FORWARD VOLTAGE DROP VERSUS TEMPERATURE

I = 1.0 a		I = 5.0 a		I = 10.0 a	
T °C	V. volts	T °C	V. volts	T °C	V. volts
23.0	0.450	23.0	0.668	24.0	0.848
24.0	0.449	24.0	0.667	25.0	0.847
25.0	0.448	25.0	0.666	26.0	0.847
26.0	0.447	26.0	0.664	27.0	0.846
27.0	0.446	27.0	0.663	28.0	0.844
28.0	0.444	28.0	0.662	29.0	0.843
30.0	0.441	30.0	0.660	30.0	0.841
32.0	0.438	32.0	0.658	32.0	0.840
34.0	0.436	34.0	0.656	34.0	0.839
36.0	0.432	36.0	0.654	36.0	0.838
38.0	0.429	38.0	0.651	37.0	0.838
42.1	0.422	40.0	0.650	40.0	0.836
45.0	0.420	42.0	0.648	42.0	0.833
46.0	0.419	46.0	0.643	46.0	0.831
48.0	0.416	48.0	0.641	48.0	0.830
50.0	0.412	50.0	0.640	50.0	0.829
52.0	0.410	52.0	0.638	52.0	0.829
54.0	0.408	54.0	0.637	54.0	0.828
56.0	0.405	56.0	0.634	56.0	0.827
58.0	0.402	58.0	0.632	58.0	0.825
60.0	0.400	60.0	0.630	60.0	0.824

TABLE XV

RECTIFIER 2 D.C. FORWARD VOLTAGE DROP VERSUS TEMPERATURE

I = 2.0 a		I = 4.0 a		I = 8.0 a	
T °C	V. volts	T °C	V. volts	T °C	V. volts
25.7	0.272	25.2	0.311	27.0	0.356
26.0	0.272	26.0	0.309	28.0	0.353
27.0	0.270	27.0	0.308	30.0	0.350
28.0	0.269	28.0	0.306	32.0	0.347
30.0	0.266	30.0	0.302	34.0	0.343
32.0	0.261	32.0	0.300	36.0	0.340
34.0	0.259	34.0	0.297	38.0	0.338
36.0	0.256	36.0	0.293	40.0	0.336
38.0	0.252	38.0	0.290	42.0	0.331
40.0	0.249	40.0	0.288	46.0	0.327
42.0	0.247	42.0	0.283	48.0	0.323
44.0	0.242	46.0	0.279	50.0	0.320
46.0	0.239	48.0	0.276	52.0	0.318
48.0	0.236	50.0	0.272	54.0	0.316
50.0	0.232	52.0	0.269	56.0	0.312
52.0	0.229	54.0	0.267	58.0	0.309
54.0	0.227	56.0	0.263	60.0	0.307
56.0	0.221	58.0	0.260		
58.0	0.220	60.0	0.258		
59.0	0.220				

TABLE XVI

RECTIFIER 3 D. C. FORWARD VOLTAGE DROP vs TEMPERATURE

I = 4.0 a			I = 8.0 a	
T °C	V, volts		T °C	V, volts
26.2	0.303		28.0	0.339
27.0	0.301		30.0	0.337
28.0	0.300		32.0	0.332
30.0	0.297		33.0	0.330
32.0	0.292		35.0	0.329
34.0	0.290		37.0	0.326
36.0	0.288		39.0	0.322
38.0	0.284		41.0	0.320
40.0	0.281		43.0	0.318
42.0	0.279		45.0	0.314
44.0	0.276		47.0	0.311
46.0	0.272		49.0	0.309
48.0	0.269		51.0	0.307
50.0	0.266		53.0	0.304
52.0	0.262		55.0	0.301
54.0	0.260		57.0	0.299
56.0	0.257		59.0	0.297
58.0	0.254		60.0	0.294
60.0	0.252			

TABLE XVII

RECTIFIER 1 60~ FORWARD VOLTAGE DROP vs TEMPERATURE

I = 1.0 a

T °C	V volts
23.0	0.455
24.0	0.452
25.0	0.449
26.0	0.447
27.0	0.446
28.0	0.445
30.0	0.442
32.0	0.440
34.0	0.439
36.0	0.437
38.0	0.434
40.0	0.432
42.0	0.428
44.0	0.426
46.0	0.420
48.0	0.419
50.0	0.418
52.0	0.416
54.0	0.414
56.0	0.412
58.0	0.409
60.0	0.406

I = 5.0 a

T °C	V volts
24.0	0.662
25.0	0.661
26.0	0.660
27.0	0.659
28.0	0.658
30.0	0.655
32.0	0.653
34.0	0.650
36.0	0.648
38.0	0.646
40.0	0.643
42.0	0.642
46.0	0.638
48.0	0.636
50.0	0.630
52.0	0.627
54.0	0.622
56.0	0.621
58.0	0.620
60.0	0.618

I = 10.0 a

T °C	V volts
23.0	0.830
24.0	0.830
25.0	0.828
26.0	0.827
27.0	0.826
28.0	0.826
30.0	0.822
32.0	0.821
34.0	0.820
36.0	0.818
38.0	0.817
40.0	0.816
42.0	0.811
44.0	0.809
46.0	0.807
48.0	0.805
50.0	0.803
52.0	0.802
54.0	0.799
57.0	0.799
59.0	0.797
60.0	0.797

TABLE XVIII
RECTIFIER 1 400~ VOLTAGE DROP (FORWARD) vs TEMPERATURE

I = 1.0 a		I = 5.0 a		I = 10.0 a	
T °C	V volts	T °C	V volts	T °C	V volts
23.0	0.452	24.0	0.657	22.0	0.847
24.0	0.450	25.0	0.658	23.0	0.846
25.0	0.448	26.0	0.657	24.0	0.845
26.0	0.446	27.0	0.657	25.0	0.845
27.0	0.443	28.0	0.656	26.0	0.844
29.0	0.440	30.0	0.654	27.0	0.843
30.0	0.438	32.0	0.650	28.0	0.843
32.0	0.434	34.0	0.646	30.0	0.841
34.0	0.431	36.0	0.643	32.0	0.839
36.0	0.426	38.0	0.641	34.0	0.837
38.0	0.422	40.0	0.640	36.0	0.835
40.0	0.418	42.0	0.637	38.0	0.832
42.0	0.416	44.0	0.634	40.0	0.829
44.0	0.413	46.0	0.629	42.0	0.827
46.0	0.408	48.0	0.626	44.0	0.825
48.0	0.403	50.0	0.624	46.0	0.822
50.0	0.401	52.0	0.622	48.0	0.821
52.0	0.398	54.0	0.620	50.0	0.819
54.0	0.396	56.0	0.617	52.0	0.818
56.0	0.393	58.0	0.614	54.0	0.815
58.0	0.386	60.0	0.612	56.0	0.813
60.0	0.380			58.0	0.811
				60.0	0.809

TABLE XIX

RECTIFIER 1 400~ -3φ FORWARD VOLTAGE DROP vs TEMPERATURE

I = 1.0 a

T °C	V volts
22.0	0.460
23.0	0.460
24.0	0.460
25.0	0.459
26.0	0.457
27.0	0.454
28.0	0.452
30.0	0.449
32.0	0.444
34.0	0.441
36.0	0.439
38.0	0.436
40.0	0.429
42.0	0.426
44.0	0.423
46.0	0.420
48.0	0.418
50.0	0.414
52.0	0.411
54.0	0.406
56.0	0.402
58.0	0.399
60.0	0.393

I = 5.0 a

T °C	V volts
25.0	0.915
26.0	0.914
27.0	0.913
28.0	0.912
30.0	0.911
32.0	0.907
34.0	0.905
36.0	0.903
38.0	0.901
40.0	0.900
42.0	0.898
45.0	0.897
46.0	0.895
48.0	0.892
50.0	0.888
52.0	0.885
54.0	0.880
56.0	0.879
58.0	0.878
60.0	0.876

I = 10.0 a

T °C	V volts
24.0	0.692
25.0	0.691
26.0	0.692
27.0	0.691
28.0	0.690
30.0	0.688
32.0	0.686
34.0	0.684
36.0	0.681
38.0	0.680
40.0	0.678
42.0	0.676
44.0	0.672
46.0	0.666
48.0	0.664
50.0	0.661
52.0	0.659
54.0	0.659
56.0	0.658
58.0	0.654
60.0	0.650

TABLE XX

RECTIFIER 1 D.C. REVERSE CURRENT vs TEMPERATURE

V = 30v

T °C	I μ amp
22.4	91.2
23.0	97.5
24.0	104.5
25.0	116.0
26.0	125.0
28.0	151.0
30.0	177.0
32.0	215.0
34.0	248
36.0	288
38.0	335
40.0	392
42.0	458
44.0	511
45.0	538
48.0	656
50.0	740
52.0	830
54.0	940
56.0	1060
58.0	1158
60.0	1283

V = 100v

T °C	I μ amp
22.0	97.5
23.0	109.9
24.0	118.0
25.0	129.0
26.0	141.5
28.0	170.0
30.0	198.6
32.0	234
34.0	274
36.0	315
37.0	343
40.0	424
42.0	492
44.0	547
45.2	595
47.0	660
50.0	792
52.0	876
54.0	981
56.0	1096
58.0	1225
60.0	1355

TABLE XXI

RECTIFIER 2 D.C. REVERSE CURRENT vs TEMPERATURE

V= 70 v

T °C	I ma
24.3	10.21
25.0	10.28
26.0	10.39
28.0	10.84
30.0	11.31
32.0	11.90
36.0	12.62
38.0	13.38
40.0	14.50
41.0	15.40
44.0	16.3
46.0	18.8
48.0	20.9
50.0	23.1
52.0	25.7
54.0	33.0
56.0	37.4
58.0	44.1
60.0	50.2

TABLE XXII
RECTIFIER 3 D.C. REVERSE CURRENT vs TEMPERATURE

V = 30v

T °C	I ma
24.1	25.0
25.0	25.6
26.0	26.0
28.0	27.3
30.0	28.3
32.0	29.2
34.0	30.6
36.0	32.3
38.0	31.1
40.0	35.9
42.0	38.9
46.0	42.4
48.0	45.0
50.0	47.7
52.0	50.0
54.0	52.2
56.0	54.9
58.0	58.0
60.0	59.9

V = 50v

T °C	I ma
24.7	38.0
25.1	38.2
26.0	38.8
28.0	39.9
30.0	41.9
32.0	43.7
34.3	45.3
36.0	46.9
38.0	48.8
40.0	51.2
42.0	54.7
43.0	57.7
46.0	58.8
48.0	62.1
50.0	64.9
52.0	68.3
54.0	72.4
56.0	76.8
58.0	81.2
60.0	85.8

TABLE XXIII

RECTIFIER 1 60~ REVERSE CURRENT vs TEMPERATURE

V = 30 v

T °C	V_R volts	I μ amp
17.2	0.309	53.2
18.0	0.369	63.5
19.0	0.415	71.4
20.0	0.460	79.2
21.0	0.500	86.1
22.0	0.580	99.8
23.0	0.634	109.1
24.0	0.693	119.2
26.0	0.848	146.0
28.0	0.96	165.2
30.0	1.16	199.7
32.0	1.42	244
34.0	1.66	286
36.0	1.93	332
38.0	2.27	391
40.0	2.46	424
42.0	2.83	487
44.0	3.20	551
47.0	3.80	654
50.0	4.51	776
52.0	4.99	859
54.0	5.57	959
56.2	6.22	1071
58.0	6.84	1177
60.0	7.54	1298

V = 110 v

T °C	V_R volts	I μ amp
17.2	0.474	81.6
18.0	0.527	90.7
19.0	0.586	100.8
20.0	0.640	110.1
21.0	0.704	121.1
22.0	0.774	133.1
23.0	0.828	142.4
24.0	0.906	155.9
25.0	1.01	165.0
26.0	1.22	173.9
28.0	1.46	210
30.0	1.77	251
32.2	2.03	305
34.0	2.38	349
36.0	2.61	409
38.0	2.99	449
40.0	3.50	514
42.0	3.90	603
44.0	4.38	671
46.0	4.97	754
48.0	5.63	856
50.2	6.20	952
52.0	6.81	1077
54.0	7.60	1172
56.0	8.34	1307
58.0	9.81	1434
60.0	10.21	1688

TABLE XXIV
RECTIFIER 1 400~ REVERSE CURRENT VERSUS TEMPERATURE

V = 30v

T °C	V_R volts	I μamp
20.9	0.526	91
21.0	0.539	93
22.0	0.607	104
23.0	0.669	115
24.0	0.738	127
25.0	0.806	139
26.0	0.869	150
28.0	1.01	174
30.0	1.17	201
32.4	1.44	248
34.2	1.63	280
36.3	1.89	325
38.0	2.11	363
40.0	2.36	406
42.0	2.86	492
45.0	3.50	602
47.0	3.85	663
50.2	4.50	774
52.0	5.02	864
54.0	5.66	974
56.0	6.48	1114
58.0	7.51	1292
60.0	8.80	1514

V = 100v

T °C	V_R volts	I μamp
18.7	0.497	86
19.3	0.563	97
20.0	0.602	104
21.0	0.645	111
22.0	0.696	120
23.0	0.768	132
24.0	0.848	146
25.0	0.918	158
26.0	1.01	174
28.0	1.21	208
30.0	1.41	242
32.0	1.65	284
34.0	1.94	333
36.0	2.22	382
38.0	2.52	433
40.0	2.86	491
42.0	3.31	569
44.0	3.66	629
46.0	4.19	720
48.0	4.74	814
50.0	5.37	924
52.0	5.96	1024
54.0	6.73	1157
56.0	7.65	1314
58.3	8.62	1482
60.0	9.82	1688

TABLE XXV

TEMPERATURE CORRECTION FACTORS FOR RECTIFIER 1 D.C. REVERSE CURRENT

$V = 30v$; $I_{22} = 84\,\mu$ amp

T °C	I_T μ amp	f_R I_{22}/I_T
23	93	0.903
24	102	0.823
26	122	0.689
28	148	0.568
30	180	0.467
33	232	0.362
36	294	0.286
40	392	0.214
43	477	0.176
46	576	0.146
50	740	0.113
53	887	0.095
56	1055	0.080
60	1278	0.066

$V = 100v$; $I_{22} = 97.5\,\mu$ amp

T °C	I_T μ amp	f_R I_{22}/I_T
23	108	0.903
24	118	0.826
26	140	0.696
28	167	0.583
30	199	0.490
33	253	0.385
36	317	0.307
40	419	0.233
43	511	0.191
46	619	0.158
50	785	0.124
53	926	0.105
56	1094	0.089
60	1352	0.072

TABLE XXVI

FINAL TEMPERATURE RISE of RECTIFIER 1 UNDER FULL LOAD WITH NO FORCED AIR

(Full wave rectifier ckt.)

Freq. c.p.s	Id.c. amp	Load Type	Filter μfd	T-final °C	T-room °C	T-rise °C
60	10.15	R	0	45.2	25.0	20.2
60	10.17	R	550	46.8	24.3	22.5
60	10.00	L	550	43.7	24.2	19.5
400	9.90	R	0	42.0	25.6	16.4
400	10.10	R	550	45.8	25.9	19.9
400	10.07	L	550	43.8	25.3	18.5

RECTIFIER 1

(Short circuit Test)

Freq. c.p.s	Ia.c amp.	T-rise °C
60	10.0	14.1
400	10.0	16.0
400, 3φ	10.0	17.5

TABLE XXVII
FORWARD D.C. VOLT-AMPERE CHARACTERISTIC of RECTIFIER 1

I, amp.	V, volts	T °C	$V_{25°}$ volts
0.10	0.281	25.1	0.281
0.30	0.350	25.0	0.350
0.44	0.380	25.1	0.380
0.80	0.428	25.0	0.428
1.23	0.468	25.1	0.468
1.54	0.492	25.1	0.492
1.81	0.509	25.2	0.509
2.03	0.523	25.2	0.523
2.58	0.552	25.9	0.553
3.00	0.576	26.1	0.577
3.53	0.600	26.3	0.601
4.01	0.622	26.8	0.624
4.30	0.634	27.0	0.636
4.98	0.661	27.3	0.663
5.63	0.688	27.8	0.691
6.01	0.702	28.1	0.705
6.51	0.720	28.3	0.723
7.18	0.746	28.8	0.750
7.54	0.758	29.5	0.763
8.40	0.789	30.0	0.794
9.08	0.812	30.4	0.817
9.70	0.832	30.7	0.838

TABLE XXVIII
FORWARD D.C. VOLT-AMPERE CHARACTERISTIC of RECTIFIER 2

I, amp	V, volts
0.01	0.033
0.25	0.182
0.50	0.211
0.75	0.227
1.01	0.240
1.26	0.249
1.50	0.256
1.99	0.268
2.49	0.278
3.00	0.287
3.51	0.297
4.01	0.303
4.50	0.312
5.00	0.321
6.00	0.326
7.03	0.339
8.00	0.353

TABLE XXIX

FORWARD D.C. VOLT-AMPERE CHARACTERISTIC of RECTIFIER 3

I, amps	V, volts
0.01	0.030
0.06	0.111
0.11	0.140
0.25	0.176
0.50	0.204
0.76	0.221
1.00	0.233
1.24	0.242
1.50	0.251
2.00	0.259
2.50	0.272
3.00	0.281
3.50	0.289
4.00	0.296
4.51	0.301
5.00	0.309
5.97	0.317
7.00	0.326
8.00	0.337
8.98	0.341
9.98	0.351
11.05	0.360
11.98	0.370

TABLE XXX
REVERSE D.C. VOLT-AMPERE CHARACTERISTIC of RECTIFIER 1

V volts	I μ amp	$I_{22°}$ μ amp	T °C
0.4	86.0	76.4	23.2
1.2	86.6	76.9	23.2
3.3	88.6	78.4	23.2
6.8	90.6	80.1	23.2
10.0	92.4	81.0	23.3
15.3	93.9	82.0	23.4
20.3	95.7	83.0	23.4
25.7	97.5	83.9	23.5
32.0	98.8	84.3	23.6
36.6	99.8	85.1	23.7
41.2	100.1	86.6	23.5
45.6	100.9	88.0	23.4
50.8	102.7	88.1	23.6
54.8	103.6	89.1	23.6
60.3	104.1	90.5	23.4
65.1	105.6	90.5	23.6
69.9	106.3	90.8	23.6
74.8	107.5	91.4	23.7
80.4	108.4	92.1	23.7
85.2	109.6	92.6	23.7
90.1	110.6	93.4	23.7
95.0	112.1	94.2	23.8
100.0	113.4	95.4	23.8

TABLE XXXI

REVERSE D.C. VOLT-AMPERE CHARACTERISTIC of RECTIFIER 1

V volts	I μ amp	$I_{22°}$ μ amp	T °C
0.8	86.8	72.9	23.8
2.2	88.0	73.9	
3.8	89.4	75.0	
6.1	90.4	75.9	
11.6	92.6	77.5	
20.5	97.0	80.9	23.9
30.3	99.6	83.1	
42.5	102.5	85.2	
51.6	104.4	86.8	
62.4	106.9	88.5	24.0
70.2	108.7	89.4	
81.2	110.7	91.0	
93.2	113.5	92.9	24.1
100.3	115.3	94.4	
110.7	117.6	96.2	
120.2	120.2	97.9	
129.4	123.5	100.5	
140.0	127.9	104.0	
150.2	132.3	107.1	24.2
160.6	138.7	112.2	
169.8	145.2	117.2	
180.7	153.9	124.1	
189.5	160.8	129.1	24.3
200.2	170.9	136.7	24.4

TABLE XXXII
REVERSE D.C. VOLT-AMPERE CHARACTERISTIC of RECTIFIER 2

V volts	I ma	I_{22° ma	T °C
5	2.27	2.25	22.9
10	2.51	2.48	
15	2.87	2.84	
20	3.30	3.26	
25	3.88	3.84	
30	4.40	4.34	23.0
35	5.00	4.93	23.1
40	5.59	5.52	
45	6.17	6.09	
50	6.70	6.60	23.2
55	7.26	7.15	23.2
60	7.79	7.66	23.3
65	8.33	8.16	23.5
70	8.89	8.70	23.6
75	9.40	9.19	23.7
80	9.91	9.67	23.8
85	10.40	10.13	23.9
90	10.91	10.63	23.9

TABLE XXXIII
REVERSE D.C. VOLT-AMPERE CHARACTERISTIC of RECTIFIER 3

V volts	I ma	$I_{22°}$ ma	T °C
5	5.6	5.2	24.4
10	9.2	8.6	24.6
15	13.0	12.4	24.6
20	16.8	16.0	24.8
25	20.8	19.9	24.9
30	24.6	23.7	24.9
35	28.9	27.8	25.1
40	32.8	31.6	25.2
45	36.7	35.4	25.3
50	40.8	39.2	25.6
55	45.3	43.4	25.9
60	49.7	47.0	26.0
65	54.7	51.9	26.8
70	60.2	57.1	27.1

TABLE XXXIV

FORWARD 60 ~ VOLT-AMPERE CHARACTERISTIC of RECTIFIER 1

I amps	V volts	$V_{22°}$ volts	T °C
0.10	0.284	0.285	23.0
0.30	0.348	0.349	23.1
0.50	0.384	0.385	23.0
0.70	0.414	0.415	23.1
1.00	0.448	0.448	22.4
2.00	0.508	0.509	22.6
3.00	0.562	0.563	22.8
4.03	0.606	0.607	22.9
5.06	0.646	0.647	23.1
6.12	0.681	0.682	23.3
7.09	0.714	0.716	23.7
8.06	0.743	0.745	24.0
9.03	0.775	0.777	24.1
10.00	0.801	0.804	24.9

TABLE XXXV
FORWARD 400~ VOLT-AMPERE CHARACTERISTIC of RECTIFIER 1

I amps	V volts	$V_{22°}$ volts	T °C
1.00	0.459	0.467	25.8
2.00	0.522	0.530	25.7
2.52	0.554	0.562	25.7
3.02	0.579	0.587	25.8
3.53	0.602	0.607	25.8
4.00	0.624	0.629	25.8
5.03	0.665	0.671	26.0
6.02	0.700	0.706	26.2
6.99	0.737	0.743	26.7
8.06	0.771	0.776	27.0
9.02	0.799	0.804	27.3
9.99	0.830	0.836	27.9

TABLE XXXVI

FORWARD 400 ~, 3 PHASE VOLT - AMPERE CHARACTERISTIC of RECTIFIER 1

I amps	V volts	$V_{22°}$ volts	T °C
1.00	0.465	0.467	24.2
2.20	0.554	0.556	24.2
2.75	0.587	0.589	24.2
3.32	0.618	0.620	24.3
3.87	0.646	0.649	24.6
4.40	0.673	0.676	24.8
4.93	0.699	0.702	24.9
5.49	0.721	0.724	25.0
6.05	0.746	0.750	25.2
7.18	0.795	0.800	25.5
7.76	0.818	0.823	25.8
8.30	0.838	0.843	26.0
8.84	0.859	0.865	26.2
9.39	0.881	0.887	26.3
9.91	0.900	0.907	26.5

TABLE XXXVII

FORWARD 60~ VOLT-AMPERE CHARACTERISTIC of RECTIFIERS 2 and 3

I amps	V volts	T °C
0.20	0.137	23.8
0.50	0.186	
0.70	0.200	
1.00	0.221	
1.24	0.234	
1.53	0.246	23.9
2.19	0.264	24.0
2.63	0.271	24.1
3.13	0.286	
3.65	0.296	
4.16	0.303	24.4
4.90	0.315	24.7
6.14	0.329	25.0
7.05	0.339	25.3
7.85	0.347	25.6

TABLE XXXVIII

REVERSE 60~ VOLT-AMPERE CHARACTERISTIC of RECTIFIER 1

V volts	V_R volts	I μamp	$I_{22°}$ μamp	T °C
0.11	0.085	14.6	13.2	23.1
0.20	0.165	28.4	25.7	
0.30	0.256	44.0	39.6	
0.43	0.357	61.4	55.3	
0.62	0.423	72.8	65.1	23.2
0.98	0.472	81.2	72.6	
2.03	0.521	89.7	80.3	
4.01	0.532	94.8	84.4	
6.00	0.564	97.0	86.4	
8.00	0.576	99.2	88.3	
10.2	0.585	100.7	89.1	23.3
15.3	0.602	103.7	91.7	
20.4	0.617	106.2	94.1	
25.3	0.628	108.0	95.7	
30.5	0.641	110.3	97.8	
39.6	0.660	113.7	100.7	
50.3	0.679	116.8	103.3	
60.2	0.697	119.9	106.2	
70.3	0.718	123.6	109.4	
80.4	0.741	127.6	113.0	
90.7	0.766	131.9	116.8	
101	0.808	138.9	123.0	
110	0.836	143.9	127.4	
120	0.882	151.8	134.3	
130	0.928	159.7	141.3	
140	0.978	168.3	149.1	

TABLE XXXIX
REVERSE 400 ~ VOLT-AMPERE CHARACTERISTIC of RECTIFIER 1

V volts	V_R volts	I μ amp	$I_{22°}$ μ amp	T °C
0.06	0.061	10.5	9.2	23.3
0.14	0.129	22.2	19.1	23.4
0.30	0.273	46.9	40.5	23.4
0.50	0.421	72.4	62.1	23.4
0.71	0.472	81.2	70.4	23.4
1.11	0.523	89.9	78.3	23.3
2.54	0.580	99.7	86.9	
5.03	0.608	104.6	90.7	
7.00	0.622	107.0	92.8	
9.92	0.638	109.7	95.2	
15.0	0.656	112.8	97.4	23.4
20.0	0.669	115.0	99 4	
25.0	0.682	117.2	100.7	
300	0.697	119.9	102.3	23.5
40.0	0.720	123.8	104.1	23.6
50.0	0.742	127.7	107.0	23.7
60.0	0.764	131.3	110.1	
70.2	0.787	135.3	113.4	
80.7	0.809	139.1	116.1	
90.1	0.833	143.2	119.4	
100	0.870	149.6	124.8	
110	0.912	156.8	130.1	23.8
120	0.951	163.5	135.7	
130	0.994	170.8	141.7	
140	1.02	175.4	145.0	

TABLE XL

D. C. RESITANCE from D. C. CHARACTERISTIC

V volts	I amp	R= V/I ohms
+0.85	+10.00	0.085
0.80	8.65	0.093
0.70	5.87	0.119
0.60	3.50	0.171
0.50	1.68	0.298
0.40	0.57	0.702
0.30	0.15	2.00
0.20	0.02	10.04
0.16	0.01	16.1

volts	μ amp	ohms/1000
− 0.8	−72.9	11
2.0	73.5	27
5.0	75.3	66
10.0	77.2	130
20	80.3	249
40	84 6	473
60	87.7	684
80	90.9	881
100	93.9	1064
120	98.1	1223
140	103.7	1350
160	111.7	1433
180	123.1	1460
200	136.4	1467

TABLE XLI

D.C. RESISTANCE from 60~ CHARACTERISTIC

V volts	I amps	$R = \frac{V}{I}$ ohms
+0.80	+10.00	0.080
0.70	6.68	0.105
0.60	3.89	0.154
0.50	1.87	0.267
0.40	0.59	0.678
0.30	0.16	1.874
0.27	0.10	2.70

volts	μ amp	$\frac{\text{ohms}}{1000}$
-0.20	-25.7	8
0.62	65.1	9
1.49	77.4	19
4.01	84.4	48
10.2	89.1	114
20	93.8	213
30	97.6	308
40	100.5	398
50	103.4	483
60	106.3	564
70	109.4	640
80	113.0	708
90	117.0	769
100	121.8	822
110	127.7	862
120	134.3	893
130	141.4	919
140	148.9	941

TABLE XLII

D.C. RESTANCE from 400~ CHARACTERISTIC

V volts	I amps	$R=\frac{V}{I}$ ohms
+0.83	+10.00	0.083
0.80	8.71	0.092
0.70	5.84	0.120
0.60	3.29	0.182
0.50	1.58	0.316
0.41	0.60	0.677
0.37	0.40	0.935
0.33	0.20	1.640
0.29	0.10	2.91

volts	μ amp	$\frac{\text{ohm}}{1000}$
− 0.06	− 9.15	7
0.21	29.3	7
0.62	70.4	9
1.11	78.3	14
2.83	87.5	32
5.98	91.6	65
9.01	94.4	96
15.0	97.2	154
20	98.8	203
30	101.7	295
40	104.2	384
60	110.0	546
80	116.0	690
100	124.1	806
110	129.4	849
120	135.1	889
130	140.8	924
140	146.8	954

TABLE XLIII
A.C. RESISTANCE from 60~ CHARACTERISTIC

V volts	ΔV volts	ΔI amps	$R=\frac{\Delta V}{\Delta I}$ ohms
+0.8	+0.263	+8.51	0.031
0.7	0.200	6.16	0.033
0.6	0.375	8.87	0.042
0.5	0.479	7.78	0.062
0.4	0.800	4.72	0.169
0.3	1.000	2.70	0.371
volts	volts	μamp	ohms/1000
− 0.1	− 0.76	−100	8
0.6	2.0	68.1	29
1.0	3.0	38.3	78
2.0	4.0	18.0	222
4.0	6.0	4.8	1250
6.0	6.0	4.8	1250
10.0	6.0	4.8	1250
20	80	32.0	2500
30	80	25.8	3100
40	100	28.4	3520
50	100	28.4	3520
60	100	28.4	3520
70	100	33.2	3520
80	80	29.0	2760
90	100	43.8	2290
100	80	40.6	1972
110	80	50.5	1584
120	76	53.0	1434
130	75	55.0	1364
140	74.6	56.3	1317

TABLE XLIV
A.C. RESISTANCE from 400~ CHARACTERISTIC

V volts	ΔV volts	ΔI amps	$R=\frac{\Delta V}{\Delta I}$ ohms
+0.83	+0.294	+9.46	0.031
0.80	0.285	8.73	0.033
0.70	0.349	10.13	0.034
0.60	0.400	8.26	0.048
0.50	0.60	7.94	0.076
0.40	0.80	4.79	0.167
0.30	1.00	2.53	0.395

volts	volts	μamp	ohms/1000
−0.3	−0.78	−98.6	8
0.7	3.00	100.4	30
1.0	4.00	65.7	61
2.0	5.00	23.2	215
4.0	40	52.4	764
6.0	60	54.3	1106
10.0	80	45.8	1746
20.0	80	26.5	3020
30.0	80	20.1	3990
40.0	80	20.2	3960
50.0	100	29.0	3450
60.0	80	24.1	3320
70.0	100	30.1	3320
80.0	80	25.1	3190
90.0	100	39.4	2540
100.0	80	40.6	1973
111.0	80	43.4	1847
120.0	80	45.9	1747
130.0	80	47.2	1700
140.0	80	47.9	1673

TABLE XLV

REGULATION, RESISTIVE LOAD ; NO FILTER

$f = 60\sim$; $V_1 = 120$ v r.m.s.

I d.c. amp	V_2 d.c. volts	T °C	V_3 *
0	53.7	25.2	
0.46	53.3		
0.89	53.2		
1.34	53.1		
1.79	53.0		
2.22	53.0	25.3	
2.67	52.9	25.3	
3.08	52.8	25.4	
3.53	52.7	25.7	
3.97	52.7	25.9	
4.43	52.7	26.0	
4.89	52.7	26.1	
5.31	52.6	26.1	
5.76	52.6	26.2	
6.62	52.4	26.6	
7.50	52.2	26.8	
8.37	52.1	27.1	
9.22	52.1	27.3	
10.08	51.8	27.7	84.0
11.23	51.8	28.1	
12.08	51.6	28.8	
13.77	51.4	29.2	

$f = 400\sim$; $V_1 = 120$ v r.m.s.

I d.c. amp	V_2 d.c. volts	T °C	V_3 *
0	53.9	25.6	
0.47	53.8	25.4	
0.92	53.4	25.5	
1.81	53.3	25.5	
2.70	53.2	25.8	
3.59	53.1	26.0	
4.48	53.0	26.2	
5.37	53.0	26.3	
6.20	52.8	26.7	
7.07	52.7	27.1	
7.92	52.7	27.6	
8.79	52.6	27.9	
9.62	52.4	28.1	83.0
10.49	52.2	28.6	
11.37	52.1	28.9	
12.18	52.0	29.1	
13.11	52.0	29.7	

* Peak to peak voltage of ripple.

TABLE XLVI

REGULATION, RESISTIVE LOAD; 240 μfd. CAPACITOR

$f = 60\sim$; $V_1 = 120$v r.m.s.				$f = 400\sim$; $V_1 = 120$v r.m.s.			
I d.c. amp	V_2 d.c. volts	T °C	V_3 *	I d.c. amp	V_2 d.c. volts	T °C	V_3 *
0	84.1	25.7		0	84.8	25.8	
0.67	77.2	25.7		0.67	77.6	25.2	
1.20	70.6	25.8	30.0	1.27	75.0	25.2	4.0
2.18	64.6	25.9		1.87	73.6	25.3	
3.08	60.3	26.0		2.42	72.1	25.3	
3.91	58.0	26.2		3.54	70.1	25.5	
4.77	56.6	26.6		4.60	68.3	25.9	
5.58	55.3	26.8		5.66	67.7	26.5	
6.39	54.7	27.2		6.68	66.3	26.8	
7.21	54.0	27.4		7.62	65.1	27.0	
8.03	53.4	27.7		8.61	64.6	27.6	
8.88	53.1	28.1		9.53	63.7	27.9	
9.68	52.8	28.3		10.46	63.0	28.2	
10.52	52.7	28.8		11.34	62.0	28.7	
11.32	52.3	29.0		12.23	61.2	28.9	
12.20	52.1	29.2		13.10	60.3	29.2	
13.01	52.0	29.6		9.97	63.1	28.1	21.0
10.11	52.8	28.8	72.3				

* Peak to peak voltage of ripple.

TABLE XLVII

REGULATION, RESISTIVE LOAD, 550 μfd CAPACITOR

$f = 60\sim$; $V_1 = 120$v r.m.s.				$f = 400\sim$; $V_1 = 120$v r.m.s.			
I d.c. amp	V_2 d.c.amp.	T °C	V_3 *	I d.c. amp	V_2 d.c. volts	T °C	V_3 *
0	83.9	22.8		0	83.9	24.2	
0.70	81.1	22.8		0.68	77.2	24.2	
1.33	79.1	22.9	14.0	1.27	74.9	24.2	1.5
2.49	74.8	23.1		1.87	73.1	24.3	
1.96	77.0	23.2		2.41	71.8	24.5	
3.54	69.7	23.6		3.54	69.6	24.8	
4.44	65.9	23.9		4.58	67.8	25.1	
5.30	63.1	24.1		5.59	66.2	25.3	
6.18	61.3	24.4		6.58	65.3	25.9	
7.03	59.9	24.9		7.50	64.0	26.2	
7.89	59.0	25.4		8.51	63.7	26.7	
8.69	58.0	25.9		9.42	62.7	27.0	
9.51	57.1	26.2		10.37	61.8	27.3	
10.31	56.3	26.7		11.26	61.2	27.8	
11.17	55.8	27.0		12.13	60.4	28.2	
11.97	55.2	27.4		13.00	59.8	28.6	
12.81	54.8	27.9		9.83	62.1	28.0	8.0
13.60	54.2	28.2					
9.97	57.1	27.0	64.6				

* Peak to peak voltage of ripple.

TABLE XLVIII
EFFECT of CAPACITANCE on 400~ REGULATION

C μfd	I d.c. amp	V_2 d.c. volts	T °C	V_3 *	Ripple Factor	Regulation %
400	9.92	62.8	30.8	13.0	0.060	74.1
550	9.83	62.5	28.0	8.0	0.037	74.1
320	9.93	62.8	29.4	14.0	0.064	74.1
240	10.00	63.1	29.3	17.0	0.079	74.4
160	10.04	63.1	29.8	29.0	0.137	74.4
80	10.18	60.8	30.0	58.0	0.329	72.4
77	10.13	60.3	30.8	58.2	0.333	71.9
70	10.02	59.7	30.8	61.0	0.352	71.1
62	9.80	58.4	30.8	63.3	0.374	69.5
61	10.18	57.7	30.9	65.0	0.389	68.7
60	10.13	57.5	30.2	67.6	0.404	68.4
58	10.12	57.2	30.7	68.0	0.407	68.1
40	9.87	53.4	30.2	77.6	0.490	63.5
20	10.08	52.2	30.2	76.0	0.495	62.1

* Peak to peak voltage of ripple.

TABLE XLIX

REGULATION; INDUCTIVE LOAD, 550 μfd CAPACITOR

$f = 60\sim$; $V_1 = 120$ v r.m.s.				$f = 400\sim$; $V_1 = 120$ v r.m.s.			
I d.c. amp	V_2 d.c. volts	T °C	V_3 *	I d.c. amp	V_2 d.c. volts	T °C	V_3 *
0	83.9	24.7		0	84.0	24.2	
2.83	60.2	24.1	47.5	2.94	70.6	24.3	2.5
4.17	57.1	24.2		4.40	67.8	24.7	
4.78	56.3	24.4		4.71	67.6	24.8	
6.03	54.6	24.8		5.08	67.1	25.0	
6.47	54.0	25.1		5.39	66.7	25.2	
7.08	53.7	25.3		6.05	65.8	25.3	
7.61	52.9	25.6		6.97	64.8	25.6	
8.70	52.4	25.9		7.64	64.2	25.8	
9.44	52.1	26.2		8.94	63.3	26.2	
10.22	51.8	26.6		10.14	62.1	26.7	
11.42	51.2	26.8		10.83	61.4	26.9	
12.51	50.8	27.1		11.31	61.2	27.3	
13.41	50.7	27.5		12.68	60.0	27.7	
10.00	51.8	27.0	74.2	13.50	59.8	28.1	
				10.03	61.8	27.3	7.5

* Peak to peak voltage of ripple.

TABLE L

EFFICIENCY, 60 ~, RESISTIVE LOAD, NO FILTER

I_1 a.c. amp	V_2 d.c. volts	I_2 d.c. amp	P_{out} watts	T °C	$P_{in\,(pri)}$ watts	Trans. Losses	$P_{in\,(sec)}$ watts	Eff. %
1.05	53.0	0.9	47.7	26.1	74	18.0	56	85.2
2.03	52.9	1.78	94.2	26.1	136	18.4	117	80.2
2.99	52.7	2.62	138	26.2	200	19.0	181	76.3
4.37	52.3	3.88	203	26.6	282	20.1	262	77.5
5.90	51.9	5.58	289	27.0	398	22.1	376	76.9
7.90	51.8	7.26	376	27.7	514	26.4	488	77.2
10.00	51.6	8.97	463	28.3	630	33.2	597	77.5
11.30	51.1	10.13	518	29.0	716	38.3	678	76.4
13.24	50.8	11.82	602	29.6	840	46.6	793	76.0
15.10	50.6	13.42	680	30.6	956	54.8	901	75.5

TABLE LI

EFFICIENCY, 400 ~, RESISTIVE LOAD, NO FILTER

I_1 a.c.amp	V_2 d.c.volts	I_2 d.c.amp	P_{out} watts	T °C	P_{in} (pri) watts	Trans. Losses	P_{in} (sec) watts	Eff %
1.06	53.7	0.91	48.8	26.4	72	13	59	82.7
2.06	53.2	1.80	95.8	26.7	134	13.5	120	79.5
4.01	53.0	3.58	170	26.9	252	15.2	237	80.2
4.95	52.8	4.43	234	27.3	312	16.6	295	79.4
6.50	52.4	6.11	320	27.9	432	19.6	412	77.7
8.5	51.8	7.77	403	28.2	548	25.3	523	77.1
10.5	51.9	9.48	492	29.0	666	33.5	632	77.8
12.3	51.4	11.11	572	29.9	782	43.0	739	77.4
14.1	51.2	12.77	655	30.8	904	52.4	852	76.9
15.1	50.9	13.54	690	31.2	960	57.2	903	76.4
10.9	51.7	9.89	502	30.8	696	35.5	660	76.2

TABLE LII

EFFICIENCY, 60~, RESISTIVE LOAD, 240 μfd CAPACITOR

I_1 a.c. amp	V_2 d.c. volts	I_2 d.c. amp	P_{out} watts	T °C	$P_{in(pri)}$ watts	Trans. Losses	$P_{in(sec)}$ watts	Eff %
3.34	67.1	1.70	114	27.4	142	19	123	92.7
4.38	62.2	2.60	162	27.8	200	20	180	89.8
5.42	58.0	3.83	222	28.1	284	21	263	84.5
7.05	55.0	5.43	299	28.7	394	24	370	80.9
8.8	53.4	7.10	379	29.7	508	29	479	79.2
11.5	52.4	9.51	498	29.8	678	39	639	77.9
14.15	51.7	11.92	618	30.9	856	51	805	76.8
15.7	50.7	13.4	680	31.5	968	58	910	74.8
11.9	52.3	9.91	518	30.1	710	41	669	77.5
2.71	70.2	1.20	84	29.3	106	19	87	96.8

TABLE LIII

EFFICIENCY, 400~, RESISTIVE LOAD, 240 μfd CAPACITOR

I_1 a.c. amp	V_2 d.c. volts	I_2 d.c. amp	P_{out} watts	T °C	P_{in}(pri) watts	Trans. Losses	P_{in} (sec) watts	Eff %
2.13	74.8	1.27	95	27.0	110	13	97	98.0
3.72	71.8	2.40	172	27.1	196	15	181	95.2
5.05	70.0	3.53	247	27.2	276	17	259	95.3
7.60	66.4	5.57	370	27.7	418	22	396	93.5
10.04	64.0	7.47	478	28.2	560	31	529	90.4
12.28	62.9	9.37	589	28.9	680	43	637	92.4
15.2	60.1	11.92	717	29.8	870	57	813	88.3
17.3	59.3	13.78	817	30.6	994	68	926	88.2
13.25	61.8	10.23	632	30.7	742	47	694	91.2

APPENDIX D

RECTIFIER SPECIFICATIONS

1. Rectifier, type 1.

Manufacturer	General Electric
Model No.	4JA3011BF1AB1

Absolute Maximum Ratings (per cell)
(60 cps, Resistive or inductive load)
(70°C Fin Temperature, 55°C ambient)

Peak Inverse Voltage	200	volts
RMS Inverse Voltage	140	volts
D.C. Output Current	5	amps
One Cycle Fault Current	150	amps
Continuous Reverse Working Voltage	100	volts
Leakage current (60 cps input)		
Peak	10	ma
Average	5	ma
Full Load Voltage Drop	0.5	volts
Power Dissipation at Full Load	3	watts
Storage Temperature	100	°C

2. Rectifier, type 2.

Manufacturer	General Electric
Model No.	6RA2DF1

Cell mounted on copper cooling fin,
fan cooled at 200 ft. per minute.

Applied Voltage	65	volts rms
D.C. Output Current	8	amps
Max. Cell Temperature	60	°C

3. Rectifier, type 3.

Manufacturer	General Electric
Model No.	6RA2CF1

Cell mounted on copper cooling fin,
fan cooled at 200 ft. per minute.

Applied voltage	50	volts rms
D.C. Output Current	12	amps
Max. Cell Temperature	60	°C

Thesis
S6657 Songer 23975
Characteristics of a germanium power rectifier operated at 400 cycles per second.